THE ELECTRICAL, STRUCTURAL AND TOPOGRAPHICAL CHARACTERISTICS OF ARCTIC SEA ICE

by

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12 February 1963

DECO Electronics, Inc.

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ILLUSTRATIONS

ACKNOWLEDGMENT

The authors would like to express their gratitude for the invaluable assistance and information provided by Dr. W. Lyon of the U. S. Navy Electronics Laboratory; Dr. A. Assur, Dr. W. Weeks, Dr. D. Duroiwa, and Mr. G. Frankenstein of the Cold Regions Research and Engineering Laboratory; Mr. J. Schule and Mr. W. Wittmann of the U. S. Navy Hydrographic Office; Dr. M. Cohn of Electronic Communications, Inc.; and by Dr. B. Levin, Mr. R. Lacy, and Mr. A. Waite of the U. S. Army Signal Research and Development Laboratory.

Special acknowledgment is also given to the New York Academy of Science for their permission to reprint excerpts and illustrations from Dr. W. Lyon's paper "Ice Research in the Arctic Ocean via Submarine", published in the June 1961 issue of the Transaction of the New York Academy of Science.

ABSTRACT

This report is a collection of pertinent information for the investigator who is interested in the electrical properties of arctic sea ice.

First, a general description is given of the nature and extent of the arctic ice cover, and the history of its geographical exploration is summarized. Then, because the known electrical data on sea-ice are very sparse, a detailed analysis is made of the factors which influence the electrical properties so that meaningful estimates of these properties may be made. The significant physical properties of sea water itself are first presented. Then the major factors present in sea-ice formation are described and the geometrical and chemical factors likely to affect the electrical properties are outlined. Following this the known electrical data are considered and anticipated trends in the electrical properties of sea-ice are discussed.

The topographical features of arctic sea-ice are next described and tabulated so that estimates may be made of the extent and thickness of the low conductivity cover over the higher conductivity sea-water.

Finally, as an aid to the research worker in this field, experimental precautions and pitfalls are listed and avenues of study are suggested. A glossary is appended, along with a listing of major ice research centers, a bibliography of major sources of information on arctic ice, and a collection of chemical definitions and techniques.

1. INTRODUCTION

It is only in comparatively recent years that the North Polar Basin has begun to yield up its secrets as the result of concerted research by the investigators of many nations. In an area where much more effort must be directed towards survival than can be spent on research, the acquisition of data has been slow and painful. Six month periods of night and extreme sub-zero temperatures make even the simplest of experiments difficult, and problems of logistics and communications are almost insurmountable. The very extent of the sea-ice cover of the Arctic Ocean presents a formidable challenge to the modern investigator. In winter, the sea-ice of the Arctic Basin covers some 8.7 million square kilometers, Defant [1961], (the area of the continental United States is approximately 8 million square kilometers) and attains an average depth of 3 to 5 meters, see Zubov [1959], over much of this area. Some idea of the mass of ice involved may be gained from the statistic that between ten and twenty thousand cubic kilometers of sea-ice are disgorged annually into the northern part of the North Atlantic Ocean, Defant [1961] and Zubov [1948]. Figure 1-1 is a map of the Arctic, showing ice limits, and the routes of some of the major explorations.

Contrary to popular opinion, the ice cover of the central arctic is not continuous, even in winter. Under the influence of wind and ocean current, ice masses achieve tremendous momentum. In subsequent collisions between these masses, extensive patterns of pressure ridges (hummocking) and cracks appear, leaving open water (leads) which later refreeze. In the brief arctic summer, the leads and polynyas (larger openings in the ice cover) are more extensive and persistent, but under no circumstances would the pack-ice of the central arctic be considered navigable to surface vessels.

The first tentative exploration efforts in the arctic were made by parties using dog sleds. Explorers such as Parry (1827), Nansen (1895), Cagni (1900) and Peary (1909) could make only the simplest of observations,

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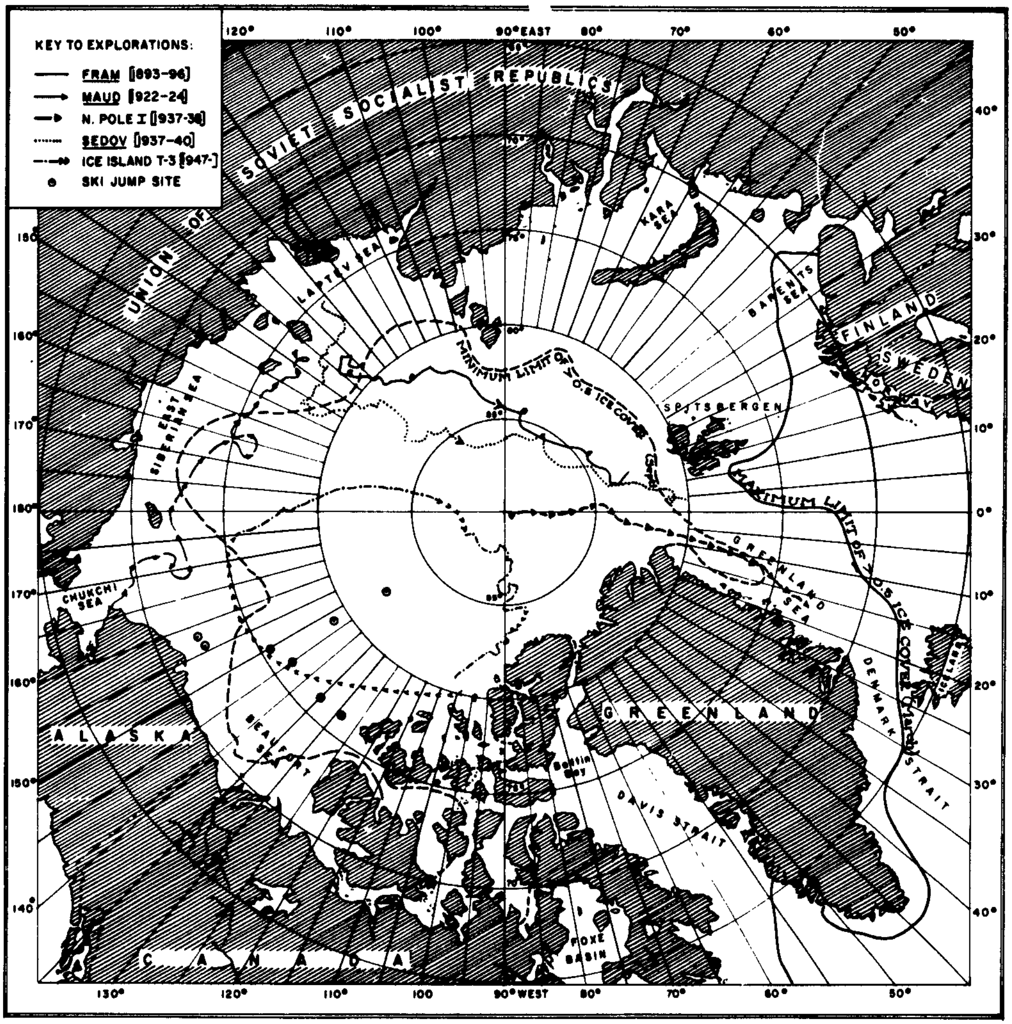

Figure 1-1 MAP OF THE ARCTIC, ITS ICE LIMITS, AND EXPLORATION ROUTES

restricted as they were by the need to travel fast and light. The most notable achievement of these early explorers was that of Peary, who, on April 6, 1909 succeeded in reaching the North Pole. Subsequent exploration by air; Byrd by aircraft (1926), Amundsen by dirigible (1926) Nobile by dirigible (1928), did not add significant amounts of data, since landings on the ice surface were not then possible. Only following 1937 when Papanin established the first of six Russian drifting "North-Pole" stations, using an airlift, and in 1951-52 when the U. S. made some 20 oceanographic stations in Project "SKIJUMP" did the use of aircraft begin to make a significant contribution to the securing of arctic data. Prior to the "North Pole" stations, and "SKIJUMP", the bulk of data on the Arctic Ocean and Arctic ice was collected by exploring vessels.

These ships, which sometimes by accident, sometimes by design, were trapped in the ice and drifted across large stretches of the Arctic, for periods of as long as three years, made possible the acquisition of large quantities of arctic data. Many notable drifts have occurred. During 1913 and 1914 the Karluk (Stefansson) drifted from Cape Barrow to Wrangel Island. The Jeannette (1879-1881) and the Maud (Amundsen) (1922-1924) drifted from Wrangel Island to the Novosibirsk Islands. The Fram (Nansen) (1893-1896) and the Russian icebreaker Sedov (1937-1940) drifted from the Novosibirsk Islands to the strait between Greenland and Spitsbergen. During 1869 and 1870 the German vessel Hansa was crushed and lost in the ice-pack but not before drifting southward almost 2000 km along the east coast of Greenland. The more important of these drifts are shown in Figure 1. Recently year-round U. S. stations have been established on the Fletcher's Ice Island T-3 (1952-1961) and the IGY Drifting Stations (1957-1958).

Finally, and subsequent to the 1931 explorations north of Spitzbergen in the conventional submarine Nautilus (Wilkins), the nuclear submarines, Nautilus, Skate, Seadragon, and Sargo, have played a role which cannot be

underestimated. In one short cruise lasting a few days, one of these ships has gathered masses of oceanographic data unthought of on conventional cruises lasting for years.

Knowledge of the Arctic Ocean and of its ice cover has advanced tremendously during the last decade. Density, temperature, and salinity data are available for large portions of the Arctic. Depth-soundings and bottom profiles are being rapidly accumulated, and many profiles of the upper and lower surfaces of the ice are available. Extensive data are on hand concerning the geographical and seasonal variations in the ice cover. In addition, the mechanical properties of sea-ice, particularly the elastic constants, have been extensively studied, both in situ and in the laboratory. An idealized model of sea-ice structure has recently been developed which shows promise for theoretical calculations, see Anderson, et al, [1958] and Assur [1958].

Data on the electrical properties of sea-ice are very fragmentary, and often lacking in the necessary data controls. The natural inhomogeneity of the ice cover results in a large scatter in the few data that are available, and much work remains to be done before our knowledge of the electrical properties of sea ice is at all complete.

In the succeeding pages, the electrical properties of the sea-water below the ice and making up the ice are first discussed. Then the present state of knowledge of the physical chemistry and the formation processes in sea-ice are presented. Following this the known electrical properties and topographical characteristics of Arctic sea-ice are summarized, along with suggestions on procedures and programs for future studies.

2. ELECTRICAL PROPERTIES OF SEA WATER

2.1 Basic Conductivity Relations in Sea Water

Sea-water is an electrolyte whose salts are almost completely dissociated. Its electrical conductivity, which depends upon both the water temperature and the salt concentration present, has been accurately determined Zubov [1931], Thomas, et al [1934], and Krümmel [1907], and found to have the following temperature dependence:

$$\operatorname{Log} \sigma_T = \operatorname{Log} \sigma_{15} + \alpha (T - 15) \quad (1)$$

where:

σ_T = sea water conductivity at temperature T°C,

σ_{15} = sea water conductivity at 15°C,

α = .01135/°C when T is near 0°C,

α = .00928/°C when T is near 25°C.

The salinity* dependence has been determined, Ruppin [1908], empirically to be:

$$\sigma = 0.0978\,S - 0.000596\,S^2 + 0.00000547\,S^3 \text{ at } 0°C \quad (2a)$$

$$\sigma = 0.1465\,S - 0.000978\,S^2 + 0.00000876\,S^3 \text{ at } 15°C \quad (2b)$$

$$\sigma = 0.1823\,S - 0.001276\,S^2 + 0.00001177\,S^3 \text{ at } 25°C \quad (2c)$$

where:

σ = electrical conductivity in mho/m, and

S = salinity in grams per thousand grams (0/00).

Equations (1) and (2) are shown parametrically in Figure 2-1. The

* For a definition of salinity, see Appendix C.

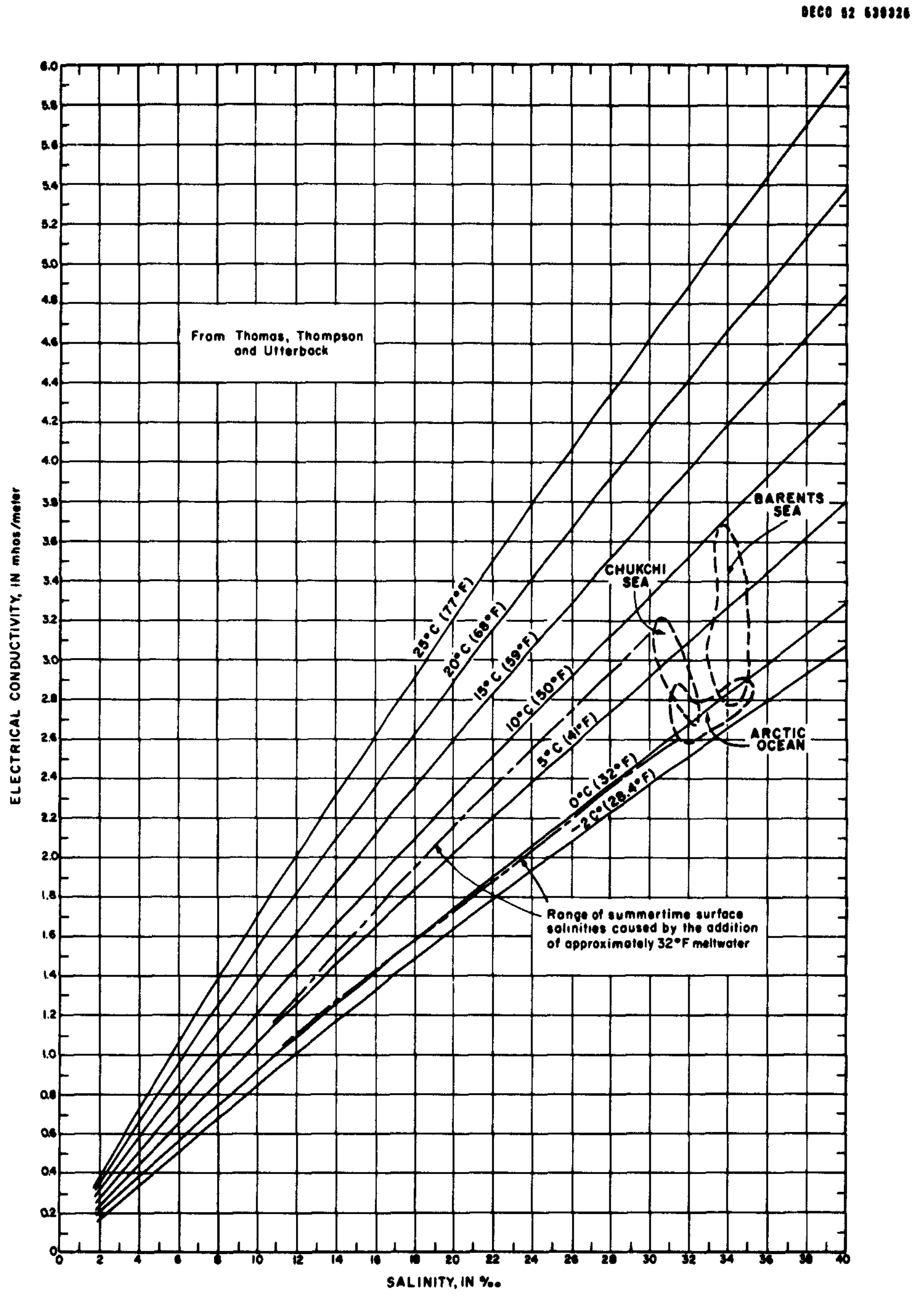

Figure 2-1 ELECTRICAL CONDUCTIVITY OF SEA WATER VS TEMPERATURE AND SALINITY

conductivity may be slightly frequency dependent. Smith-Rose [1933] reports a 40% rise between 500 c/s and 10 mc/s.

2.2 Electrical Properties through a Vertical Section of the Arctic Ocean

Salinity and temperature profiles, and in some cases whole contours, have been determined, U. S. Navy, H. O., [1958], for many stations in the Arctic Ocean. These data come from a variety of sources: submarine and icebreaker cruises, Ice-Island and operation "SKIJUMP" stations, and drifting, ice-locked exploration ships. A combination of these temperature and salinity data with the conductivity relations of Figure 2 then allows conductivity profiles or contours to be constructed.

2.2.1 Temperature and Salinity Contours

Figures 2-2a and 2-3a show temperature contours, and Figures 2-2b and 2-3b show salinity contours, for vertical sections through the Chukchi and Barents Seas, respectively. The Chukchi Sea contours show cold water, in general, overlying warmer water and a relatively low surface salinity increasing considerably with depth. The Barents Sea contours, on the other hand, show warm water overlying colder water and a relatively constant salinity.

2.2.2 Electrical Conductivity Contours

From Figure 2-1 it is apparent that a change of 1 0/00 in salinity produces the same conductivity change as would a change in temperature of approximately 2°F. The temperature contour intervals in Figures 2-2a and 2-3a are 2.5°F and the salinity contour intervals in Figures 2-2b and 2-3b are 0.25 0/00. Hence, the change in conductivity between adjacent temperature contours (assuming salinity constant) is five times as great as the change in conductivity between adjacent salinity contours (assuming temperature constant). Thus for regions where isotherms and isohalines are approximately the same distance apart, lines of constant conductivity will, to a first approximation, follow the isotherms. The influence of salinity may then be considered as a perturbation to this first approximation.

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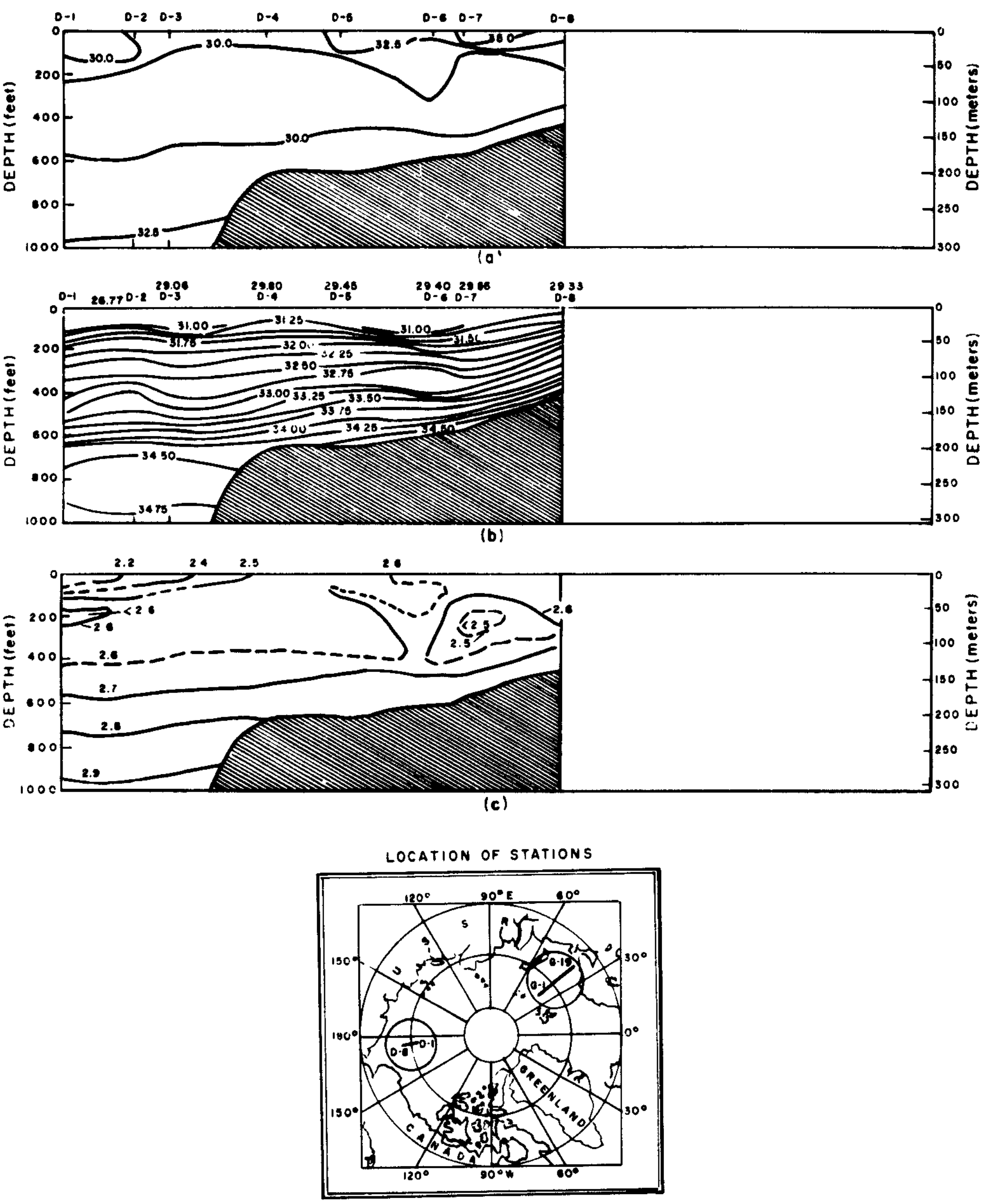

Figure 2-2 TEMPERATURE, SALINITY, AND CONDUCTIVITY CONTOURS CHUKCHI SEA

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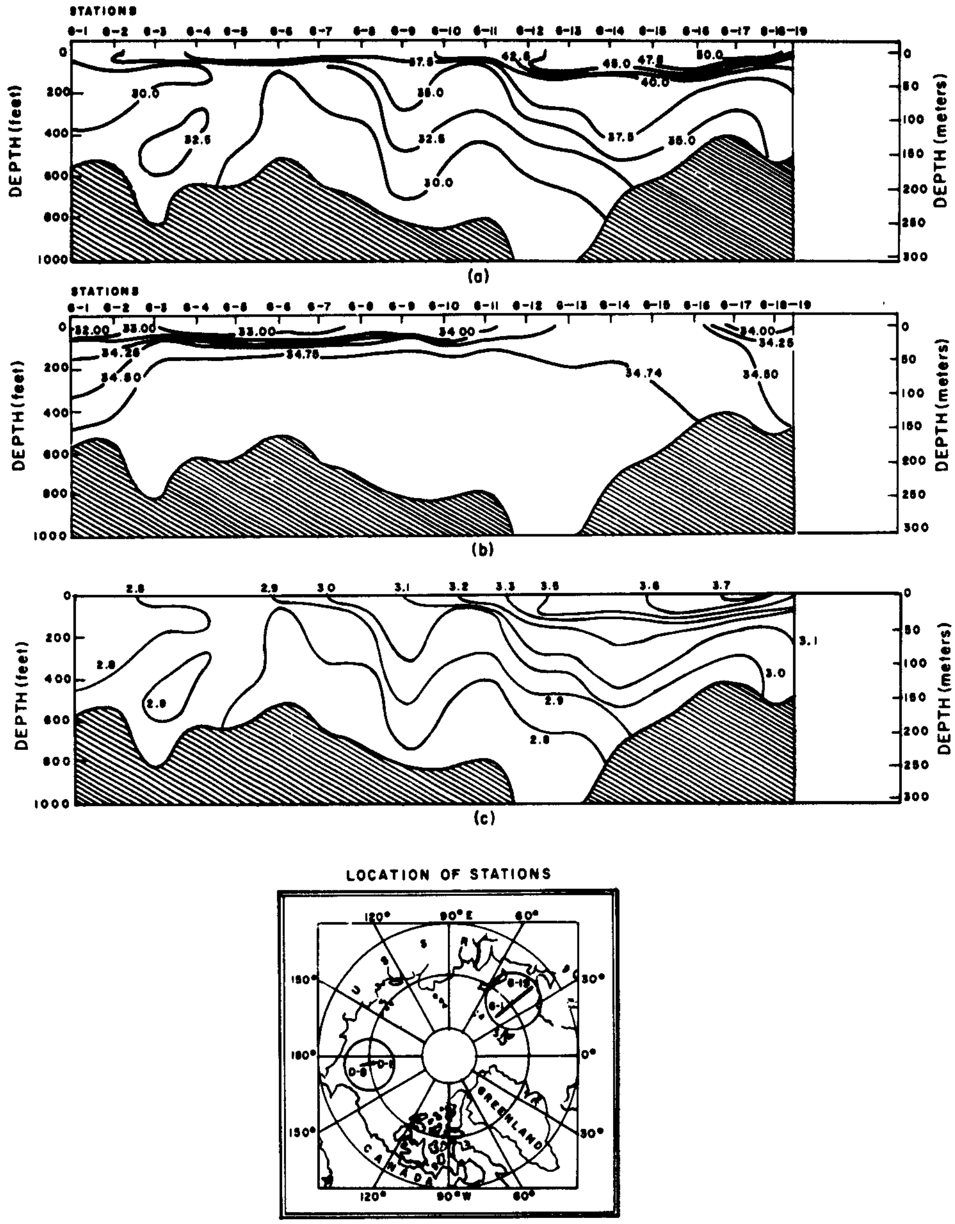

Figure 2-3 TEMPERATURE, SALINITY, AND CONDUCTIVITY CONTOURS
BARENTS SEA

If the temperature and salinity gradients have the same sign, lines of constant conductivity will not swing as far into zones of higher or lower salinity, as do the isoltherms. However, if the temperature and salinity gradients have opposite sign, lines of constant conductivity will make larger excursions into zones of higher or lower salinity than do the isotherms.

Figures 2-2c and 2-3c show approximate conductivity contours for the vertical sections through the Chukchi and Barents Seas. These contours possess less accuracy than do those of temperature and salinity since estimates must be made of the gradients between temperature and salinity contour lines. For this construction, a linear interpolation was used.

In the region north of Bering Strait (Figure 2-2c) the ocean conductivity varies fairly uniformly from about 2.2 mho/m at the surface to above 2.9 mho/m at the bottom. Over the continental shelf a zone of conductivity > 2.6 mho/m penetrates to the surface. In the Barents Sea (Figure 2-3c) on the other hand, the conductivity is highest at the surface (> 3.7 mho/m) and decreases rather regularly with depth to a bottom of < 2.8 mho/m.

3. GENERAL DESCRIPTION OF SEA ICE

3.1 Physical Chemistry of Sea Ice

Any basic understanding of the physical properties of sea-ice is intimately associated with a knowledge of the properties of the sea-water from which the ice is formed, and an understanding of the rather complex chemical and structural changes which occur in sea-ice as a function of its temperature, thermal history, and age.

The initial freezing process is quite different from that occurring in fresh water. Sea-water contains large quantities of dissolved salts and, as a result, the freezing point of the water will be depressed by an amount which depends on the concentration of salts in the water. Also, since the density of sea-water depends on the amount of dissolved salts present in the water, both the density and the temperature at maximum density will depend on the salinity of the sea-water.

When the sea-water does begin to freeze, it solidifies in the form of a matrix of pure ice (essentially salt-free) containing pockets of highly concentrated brine. If the temperature of the ice is further lowered, more and more water freezes out of the brine cells, leaving behind brine of such a concentration that salts actually begin to crystallize out. However, even at temperatures as low as -50° C, traces of brine still remain.

3.1.1 Effect of Salinity on the Freezing Point and on the Temperature at Maximum Density of Sea Water.

Figure 3-1 shows the freezing point depression of sea-water caused by the salts which it contains in solution. This depression is almost directly proportional to the salinity down to about -8.2°C. The breaks in the curve, caused by the precipitation of certain salts, will be more clearly illustrated in Figure 3-3.

In Figure 3-2, the freezing point depression for low salinities is compared with the curve showing the practically linear dependence of the temperature

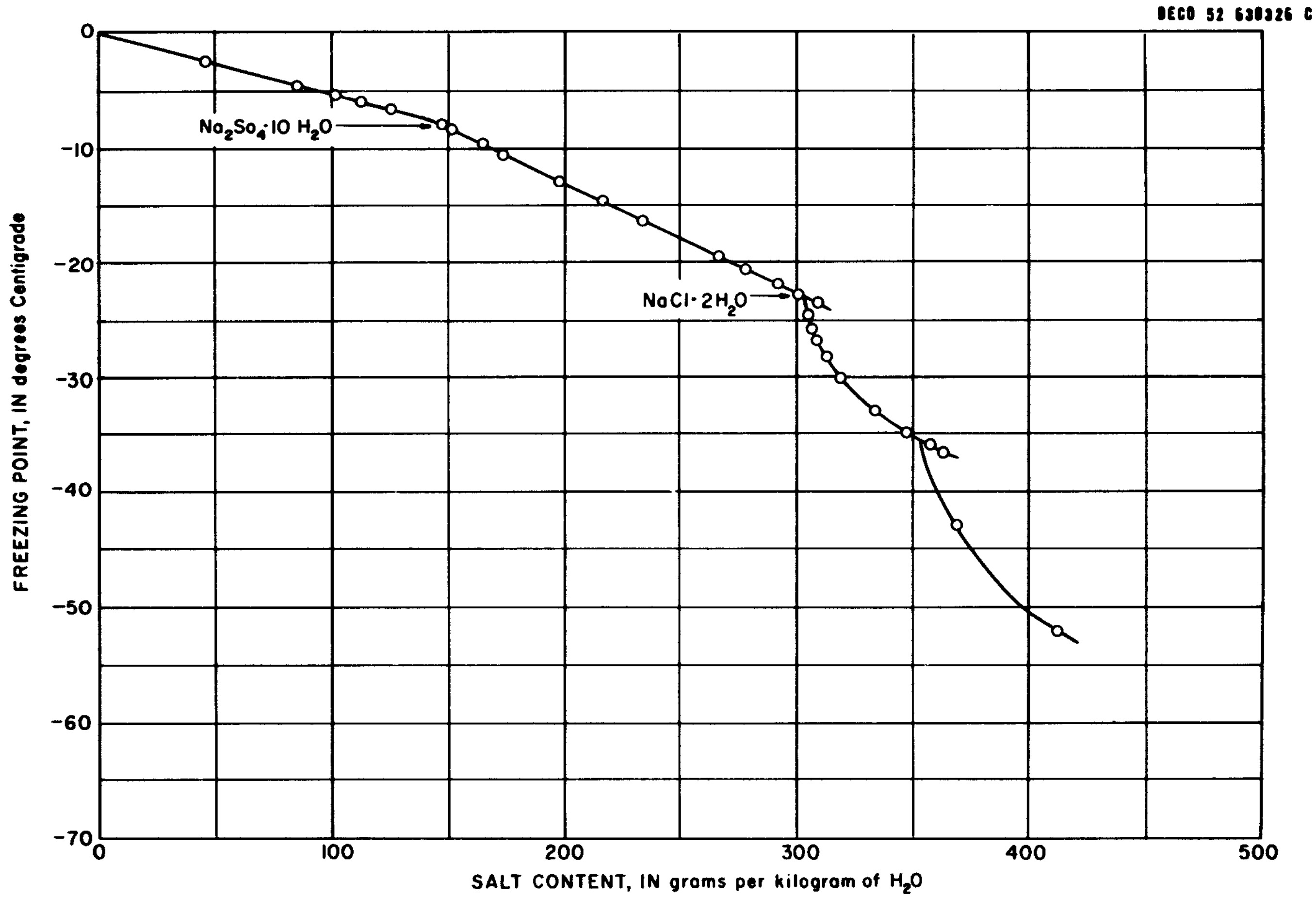

Figure 3-1 FREEZING POINT OF BRINE VS RATIO OF DISSOLVED SALTS TO PURE WATER

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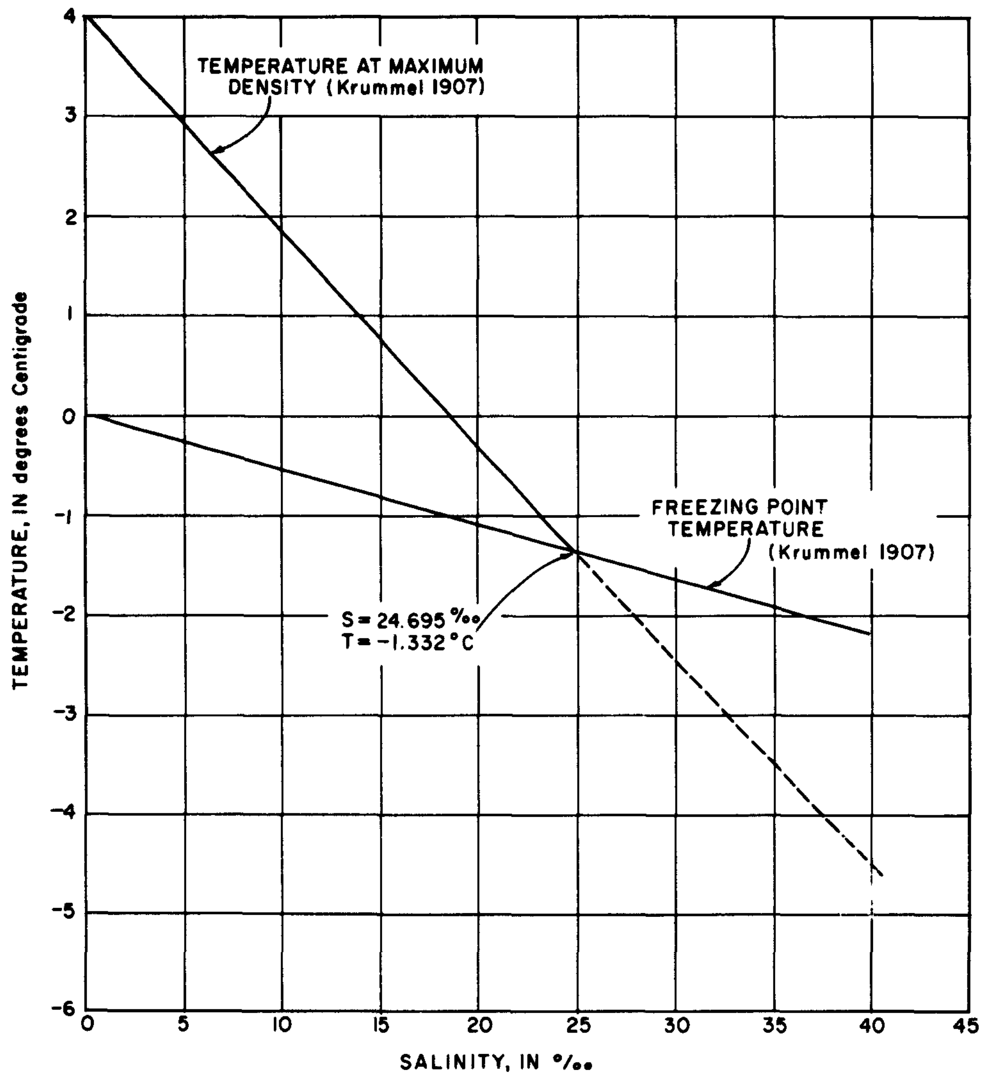

Figure 3-2 FREEZING POINT AND TEMPERATURE AT MAXIMUM DENSITY VS SALINITY OF SEA WATER

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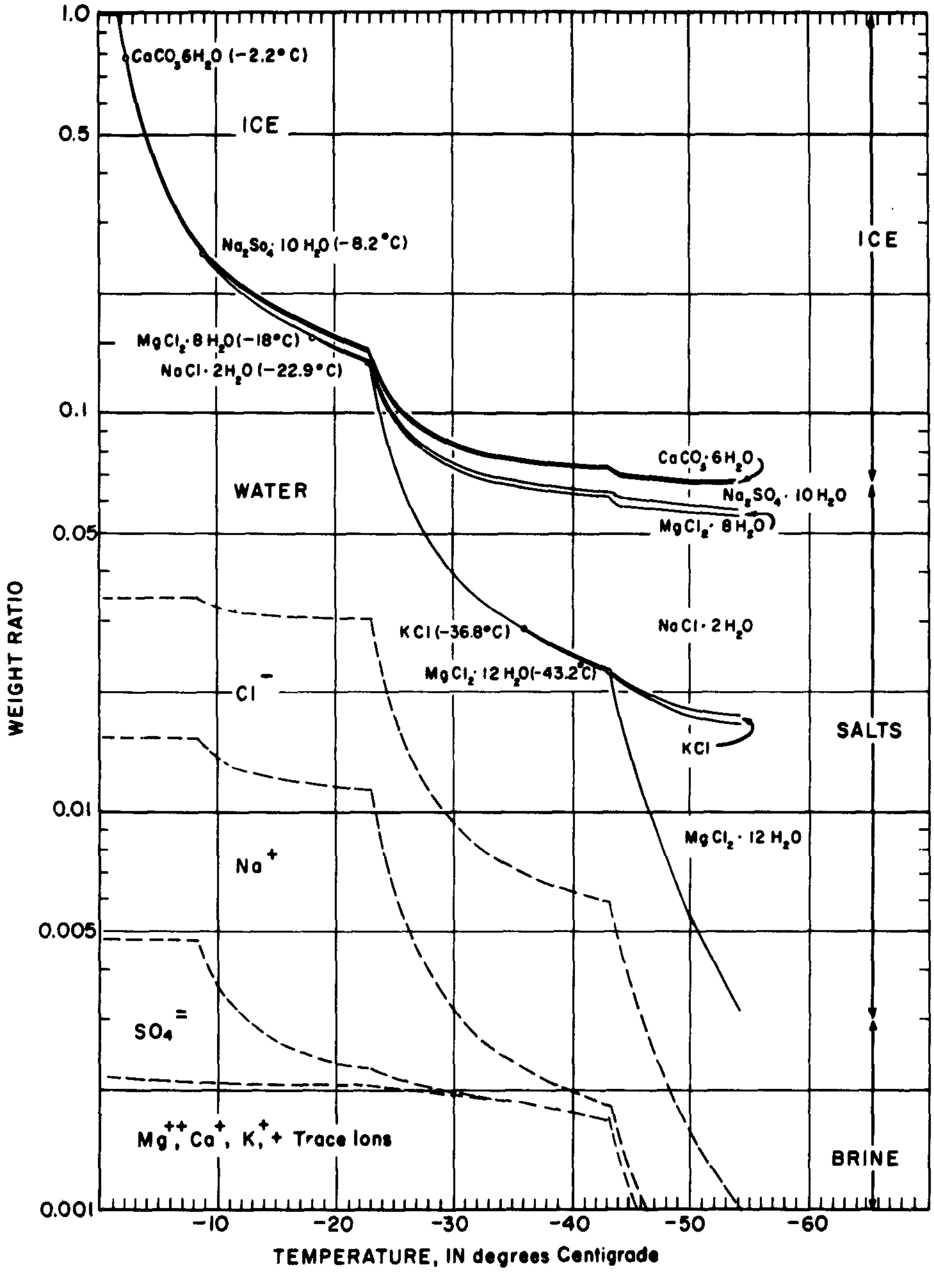

Figure 3-3 PHASE DIAGRAM OF SEA ICE, SALINITY 32.54 0/00

at maximum density, T_D, upon the salinity of the water. For pure water, the maximum density occurs at +3.98° C, but as the salinity is then increased, the maximum density occurs at lower and lower temperatures, until, above a salinity of 24.695 0/00* T_D would theoretically be lower than the temperature at which ice formed. This property of freezing sea-water is significant in some of the freezing processes discussed in Section 3.3.

3.1.2 Phase Diagram for Sea Ice

Sea-ice is a mixture of pure ice, brine, solid salts, and air in proportions and in spatial arrangements determined by the temperature and by the thermal history of the sample. Although the phase relations for sea-ice have never been determined in detail experimentally, they may be deduced indirectly from a knowledge of the concentration of the principal ions present at a given temperature, Nelson et al [1954]. Such a phase diagram, deduced by Assur [1958] and Anderson [1961] is shown in Figure 7 for sea-ice whose salinity is 32.54 0/00.

As sea-water is cooled, the temperature at which solidification first occurs is determined by the salinity of the water, as shown in the freezing point curve of Figure 3-1 or Figure 3-2. At this temperature, the only solid which forms is pure ice, Nelson et al [1954]. As the temperature is further reduced, brine, which is pocketed between the pure ice crystals, becomes increasingly concentrated as more and more water is frozen out of solution. Finally at -2.2° C, the brine concentration becomes sufficiently high, and the temperature sufficiently low that $CaCO_3 \cdot 6\,H_2O$ begins to crystallize out of the brine. At still lower temperatures, other salts begin to crystallize out. The principal ones are: $Na_2SO_4 \cdot 10\,H_2O$ at -8.2° C, $MgCl_2 \cdot 8\,H_2O$ at -18° C, $NaCl \cdot 2\,H_2O$ at -22.9° C, KCl at - 36.8° C, $MgCl_2 \cdot 12\,H_2O$ at -43.2° C and $CaCl_2 \cdot 6\,H_2O$ at -54° C.

* 0/00 is the symbol for parts per thousand.

The differential precipitation of salts and the inclusion of water of hydration in these salts results in two interesting developments. One, brine drainage from the sea-ice at a given temperature will result in a shift in the ratios of the various ions remaining behind. Two, the presence of water of hydration in the precipitated salts results in a solid salt content in sea-ice which is greater than the salinity of the sea-ice meltwater.

3.1.3 Brine Volume as a Function of Temperature and Salinity

While Figure 3-3, which indicates the relative weights of the various constituents in ice of a given salinity, is most useful for depicting the actual physical changes occurring, many of the useful physical properties of sea-ice are influenced primarily by the relative volumes of ice, brine, and salts, regardless of what the particular weight may be. For this reason, Anderson and Weeks [1958] have determined the brine content by volume, for various salinities down to about -20°. The results are shown in Figure 3-4. Below -22.9°C there is a change in the slope of the curves due to the precipitation of rather large amounts of $NaCl \cdot 2H_2O$. The amounts of $MgCl_2 \cdot 10H_2O$ precipitated at -8.2°C are smaller, and do not noticeably affect the slopes at this point.

3.2 Description of a Typical Sea Ice Formation Sequence

While sea-ice may form and age in different ways under different ambient conditions, a very typical formation sequence has been outlined by Anderson and Weeks [1958] and by Weeks [1958].

In the initial stages of sea-ice formation, once the freezing point has been reached, small crystals of pure ice appear, usually in the form of squarish platelets or circular discoids, running up to 2.5 cm in diameter and from 0.1 mm to 1 mm in thickness. Sometimes under conditions of very rapid cooling the initial crystals will have hexagonal, snowflake-like dendritic shapes.

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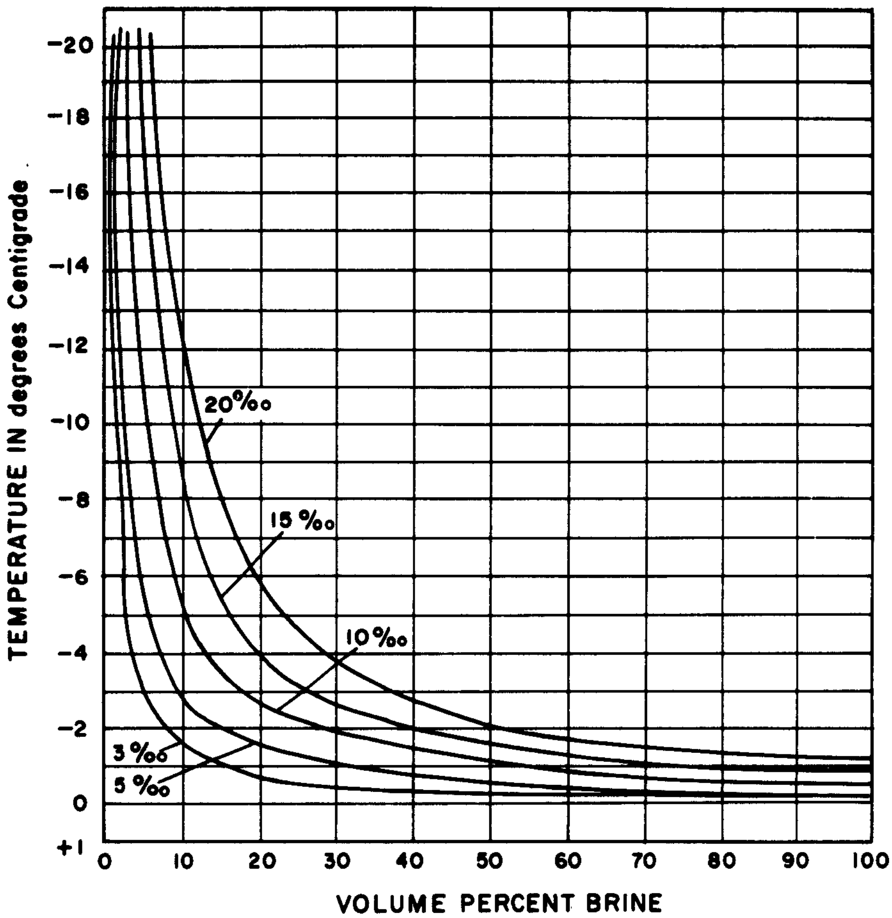

Figure 3-4 VOLUME PERCENT OF BRINE VS TEMPERATURE FOR VARIOUS SALINITIES

The ice platelets lie with their 0001 planes* parallel to the water surface, and hence have vertical c-axes. As the result of accretion the floating platelets overlap, forming a mush which eventually solidifies, trapping brine in the spaces between them in the form of more or less vertical, parallel sheets. With a further temperature decrease, and under the influence of surface tension, these brine sheets become narrow in spots, and eventually form into rows of vertical cylinders of elliptical, or finally circular cross-section. Furthermore these vertical cylinders of brine, which maintain their vertically elongated form because of gravity and because of the vertical thermal gradients normally found in sea-ice, migrate vertically under the influence of the changing thermal gradients to the region of higher temperature (to the bottom in winter and to the top in summer). Every migration to the ice-water interface results in brine drainage which in turn results in an overall decrease in the salinity of the ice block. Migration of the brine cells to the ice-air interface in the summer causes concentration of the brine by water evaporation, and occasionally, formation of salt crystals.

Anderson and Weeks [1958] have published photomicrographs of these brine cells. These are shown in Figure 3-5. The dimensions of the cell structure are surprisingly regular. The platelet width varies between 0.4 and 0.5 mm with an average value of .46 mm. The cylinder diameter is proportional to the square root of the relative brine content by volume. Typical values for cell diameter are .07 mm for ice of salinity 20 0/00 at -10°C and .03 mm for ice of salinity 5 0/00 at -10°C.

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* The crystallographic structure of ice shows each oxygen atom of the water molecule surrounded tetrahedrally by four other oxygen atoms. The smaller hydrogen atoms lie on the lines joining the oxygen atoms. The base plane of this prismatic arrangement is designated the 0001 plane according to the Bravais Index system of nomenclature. The c-axis, perpendicular to this plane, is the optic-axis of the crystal. It can be located by etch-pit or polarographic techniques.

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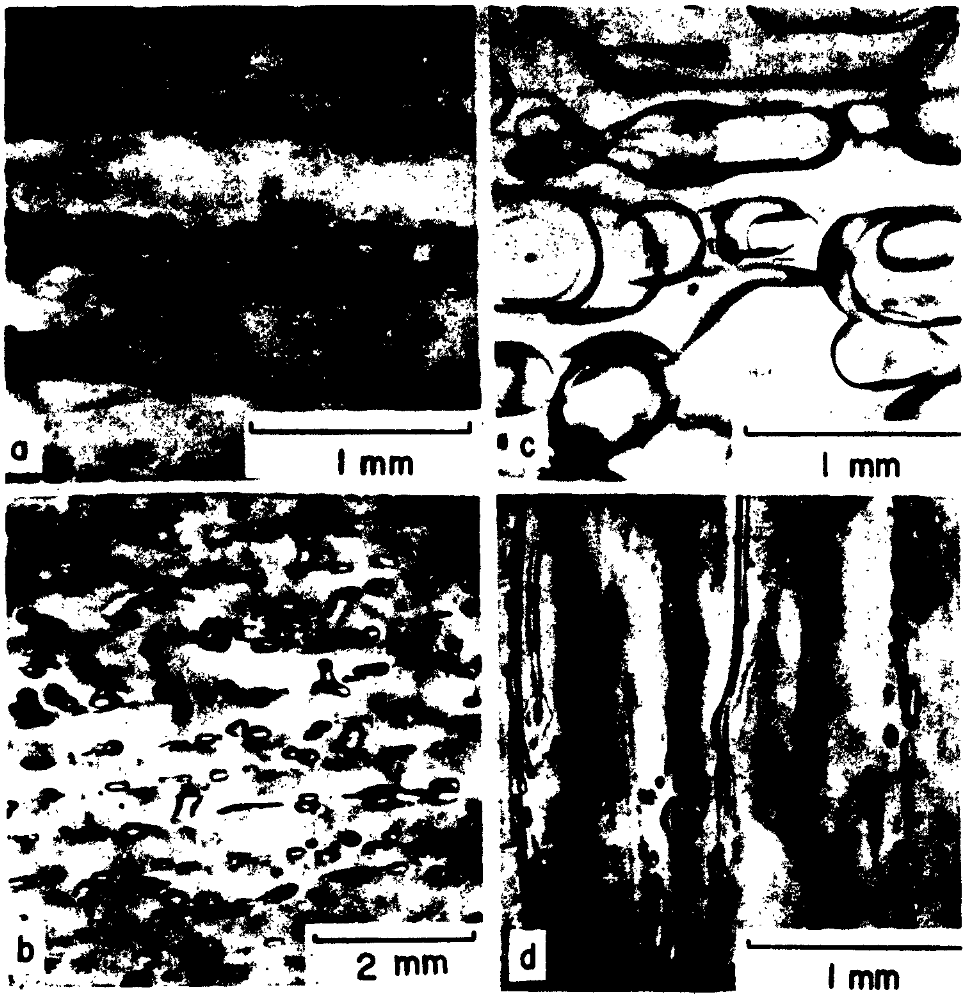

Figure 3-5 PHOTOMICROGRAPHS OF SEA-ICE STRUCTURE

3.3 Additional Factors which can Influence Sea-Ice Formation

While the preceding discussion presents the ice formation process in broad outline, many variants of this process actually occur in nature. Depending upon the local initial conditions of salinity, sea roughness, air temperature, and snowfall, the basic ice formation process may be modified in several ways. Subsequent to the formation of the ice, the local conditions of weather and ice-pack circulation may also cause modifications in the basic aging process.

With increasing attention to details of the ice structure, more and more modifying factors must be considered. The following modifying factors are merely the most important encountered.

a) The significance of the salinity value 24.695 0/00 in Figure 3-2

Whenever sea-water above +3.96°C is cooled from above, it will increase in density, and sink. Thus, vertical convection will occur, and if a layer of uniform salinity exists, the temperature throughout the entire layer will drop as a result of the cooling.

If the salinity is below 24.695 0/00 the layer will achieve its maximum density before reaching the freezing point and convection will temporarily cease. Further cooling will reduce the temperature of the surface water only, and the top layer will begin to freeze in the same way that the top layer of fresh water freezes. Since only pure ice* is frozen out of the solution, the initial

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* The question of the "purity" of ice is to some extent a question of semantics. Whether salt water ice or fresh water ice is under discussion, the crystals which form appear to have very low impurity concentrations. In the case of sea-ice, the salt impurities are left behind in the brine pockets. In the case of fresh ice, the impurities are rejected by the growing crystal and are found in the grain boundaries surrounding the crystal. A few, very unique impurity types of just the correct atomic size may exist within the fabric of the crystal, either substitutionally or interstitially (e.g. NH_4F), but in general, impurities will not be built into the growing crystal. Thus the difference between fresh ice and sea-ice may be one of degree rather than kind. There is also good evidence for structural similarities between the two types of ice. The study of internal melting of fresh ice reveals a layered structure, with migrating rows of spherical and cylindrical cavities, all lying in planes perpendicular to the c-axis of the crystal. These planes are approximately 0.5 mm apart. (See, for example: U. Nakaya, Properties of Single Crystals of Ice Revealed by Internal Melting, SIPRE Research Paper 13, (April, 1956)).

freezing raises the salinity of the sea-water surrounding the new ice. The enhanced salinity then triggers a new cycle of convection to a lower T_D. This cycling continues as long as cooling persists and ice continues to form.

If the salinity is greater than 24.695 0/00 (the usual case in the Arctic Ocean) the freezing process is different. Vertical convection will still occur, but the entire layer will now reach its freezing temperature before the convection process has ceased. Thus, ice can form at any depth in the layer and then float to the surface.

It should be noted that since the ice formed is essentially pure, its formation enhances the salinity of the surrounding sea-water. It is this enhanced salinity which temporarily prevents further freezing and leads to the formation of separate ice platelets instead of a continuous surface ice crust or a continuous sub-surface ice fabric.

In the Arctic Ocean both types of salinity conditions can occur. The salinity will exceed 24.695 0/00 in the winter but in the late summer, fresh meltwater from the ice pack will reduce surface salinities to values much below 24.695 0/00. Salinities as low as 5.97 0/00 have been observed immediately below the ice, Gagnon [1961], increasing approximately linearly to normal arctic sea water values in the first 5 meters of depth.

b) Effect of Wave Motion on Ice Formation

Ice formed during periods of wave action is generally called "pancake ice", or sometimes "spongy ice". If it is formed under calmer conditions it is called "sheet ice", "ice rind", or occasionally "needle ice".

Pancake ice is the direct result of wave action. Usually, the initial platelets or dendrites form throughout a surface stratum of the sea and float to the surface. There they are broken up by wave action into a mush of crystal fragments. As freezing continues, the mush solidifies into blocks 20 cm to 400 cm across and some 8 to 10 cm thick. These blocks abrade one another under the influence of wind and wave until they take on a pancake-

like appearance. They often have raised edges caused by the freezing of waves lapping at their edges. These pancakes will eventually be cemented together, either by subsequent mush formation in rough weather or by sheet-ice formation in calm weather. The result is a very heterogeneous assemblage of ice crystallites and brine pockets, with ice c-axes and brine pocket axes randomly oriented.

Sheet ice formation only occurs in calmer weather. Platelets which float to the surface soon become cemented together into a smooth unbroken surface a few millimeters thick. The platelets normally float with vertical c-axes. Depending upon the degree of calmness of the water, a certain fraction of these c-axes will become tilted during the cementing process. Weeks [1958] reports from 90% to 10% vertical c-axes for smooth or relatively rough seas respectively.

The amount of brine occluded in the ice will naturally be larger if freezing occurs during periods of heavy wave action.

Once the initial ice cover has formed, growth takes place on the bottom surface of the ice. Those crystals which do have horizontal c-axes tend to grow more rapidly than do those with vertical c-axes. This is because the crystals are not isotropic in thermal conductivity. Those with horizontal c-axes have their direction of maximum thermal conductivity parallel to the direction of heat flow and hence grow more rapidly. Only 5 centimeters of growth downward is necessary in order to achieve essentially complete horizontal c-axis orientation. Below this level the diameter of the largest of these preferred crystals with horizontal c-axes will continue to grow at the expense of the others. Thus the fabric of an ice sheet will consist of vertically elongated crystals extending from the bottom to the underside of the initial surface. These crystal diameters vary from a few millimeters to as high as 20 cm. Within the crystal of course, brine cells can occur in vertical layers, approximately 0.5 mm apart.

c) Effect of Freezing Rate on Ice Salinity

Rapid freezing rates result in maximum trapping of brine. Slow freezing rates, on the other hand, permit seepage of brine before solidification is complete. As the ice thickness increases, the heat flux is reduced. The consequent slowing in the growth rate results in a lower salinity in the bottom layers of the ice sheet than in the top layers. The reduction in salinity in the bottom layers of the ice sheet may to some extent be offset by brine migration from above. This downward migration of brine is caused partly by gravity, and partly as a consequence of the brine cell migration described in Section 3. 2.

d) Effect of Snowfall on the Ice Sheet

Snow cover on top of the ice, can over a period of time, crystallize into an ice layer which may be fresh or highly saline, depending upon ambient conditions.

The high salinity crystallized snow cover is formed in the following way: If the load of snow is sufficiently great, the top of the ice sheet may be forced below sea level. Brine present in the existing ice can then flood the snow layer. A salty slush layer is thus formed throughout part or all of the snow layer. Subsequent freezing then results in highly saline ice.

If the ice surface is not depressed below sea level, or if the temperature is sufficiently low that brine cells in the ice are not interconnected, then no brine flooding of the snow layer can occur. However, whenever the temperature becomes sufficiently high that the ice becomes permeable to brine or sea-water, the converse will be true. For ice of typical salinity 6 0/00 to 8 0/00, the critical temperature for this process is around -3°C or -4°C, see Weeks and Lee [1958].

A certain amount of salinity in the snow cover may also be introduced by the snowflakes themselves. The air over the Arctic Ocean undoubtedly contains many salt nucleii, introduced not only by violent wave action at the

water surface, but also by brine evaporation and subsequent wind action on the ice surface itself. These salt nucleii in the air then serve as condensation nucleii around which raindrops or snowflakes can form. While no direct evidence for such slightly saline snowflakes has been found, electrical measurements by Watt and Maxwell [1960] on Greenland glacier ice show an abnormally high conductivity at low frequencies which may be caused by such occluded salts.

Whether the snow crystallizes into salt or fresh ice, the crystallites have predominantly vertical c-axes consistent with the usual c-axis orientation at the top surface of the existing ice.

e) Effect of Accretion and Ablation

It is meaningless to consider a given sample of ice as possessing a unique identity throughout its lifetime. During the arctic summer the absorption of radiation, mostly in the top layers of the ice results in surface melting. Some 30 to 80 cm of top ice are lost by ablation each summer, even in the most northerly regions of the arctic pack. During the following winter, anywhere from 50 cm to 250 cm of the low salinity ice will build up on the underside of the existing ice. The rate of accretion in a given geographical location is governed by the residual ice thickness at the end of the previous summer. Zubov [1959] has estimated that very old ice will reach an equilibrium thickness of approximately 500 cm with approximately 50 cm of ice being lost and gained each summer and winter, in the ablation and accretion processes.

f) The Nature of the "Skeleton Layer"

Assur, in a private communication, has described the existence of a 2.4 cm to 2.8 cm "skeleton layer" on the underside of growing ice. In this growing zone, the vertical ice platelets are unconnected. Anderson and Weeks [1958] have shown that the transition from unconnected platelets (brine sheets) to connected platelets (brine cylinders) occurs at a brine concentration of 15.2%

by volume. Presumably, therefore, this skeleton layer is a zone of brine concentration > 15.2% by volume. By its very structural nature, however, this zone will be subject to excessive brine drainage if samples are removed from this zone for test purposes.

g) Ice Crystal Reorientation Effects

The densities of sea-water and sea-ice are such that normally, about one seventh of the ice floats above the surface. If the brine cells of the ice are connected, that portion of the ice above the water surface will be drained relatively free of brine, while that portion below the surface will at least have sea-water in the cells. If, for any reason, the ice is raised or tilted, the brine and salt water distributions, and the drainage patterns will be greatly modified.

Under the influence of wind and current, ice fields will grind together. Broken, tumbled, piles of ice called "pressure ridges" will form at the contact zone. These zones will therefore be zones of irregularly oriented crystals, containing many voids. Over a period of time, creep will occur in the ice, the jumbled piles will partially sink as isostatic equilibrium is reestablished and large underwater projections will appear with a depth governed by the average density of the void filled ice. It is apparent that, as brine and salt water seep into the voids between these irregularly oriented crystals, the final solidified structure will bear little resemblance to the more orderly structures described in previous sections.

3.4 Temperature and Salinity Profiles

Figure 3-6 shows typical temperature profiles for different periods of the year. The thermal conductivity of the ice is so low only the upper three or four meters of the ice sheet experience the effects of seasonal cooling and heating. Below this level, the temperature seldom varies more than a few tenths of a degree from the temperature of the sea water.

Figure 3-7 shows typical variations in salinity for sea-ice covered with slush ice and for sheet ice, Weeks and Lee [1962]. Figure 3-7a shows the first week of brine drainage in a specimen of sea-ice covered with frozen

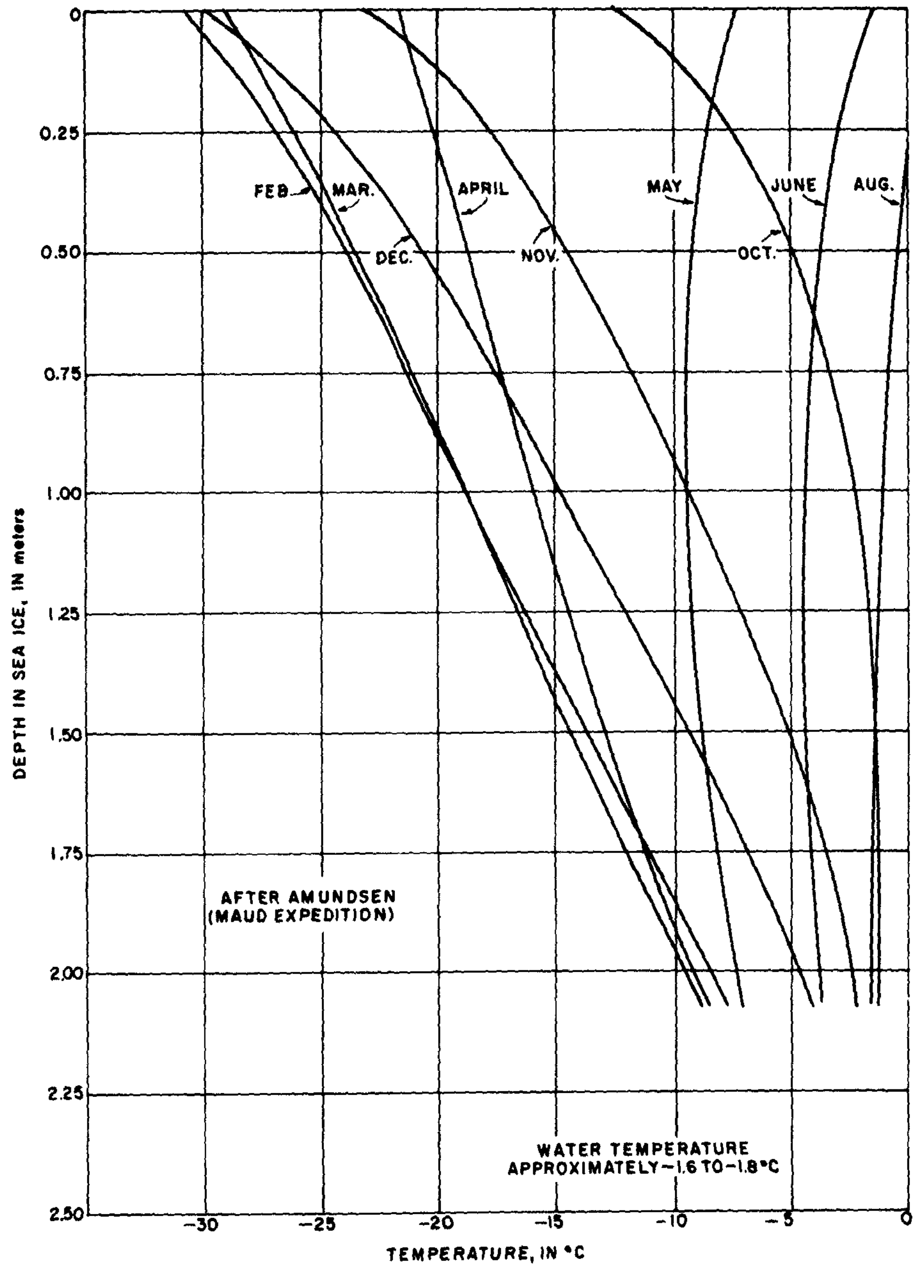

Figure 3-5 TEMPERATURE PROFILES IN SEA-ICE

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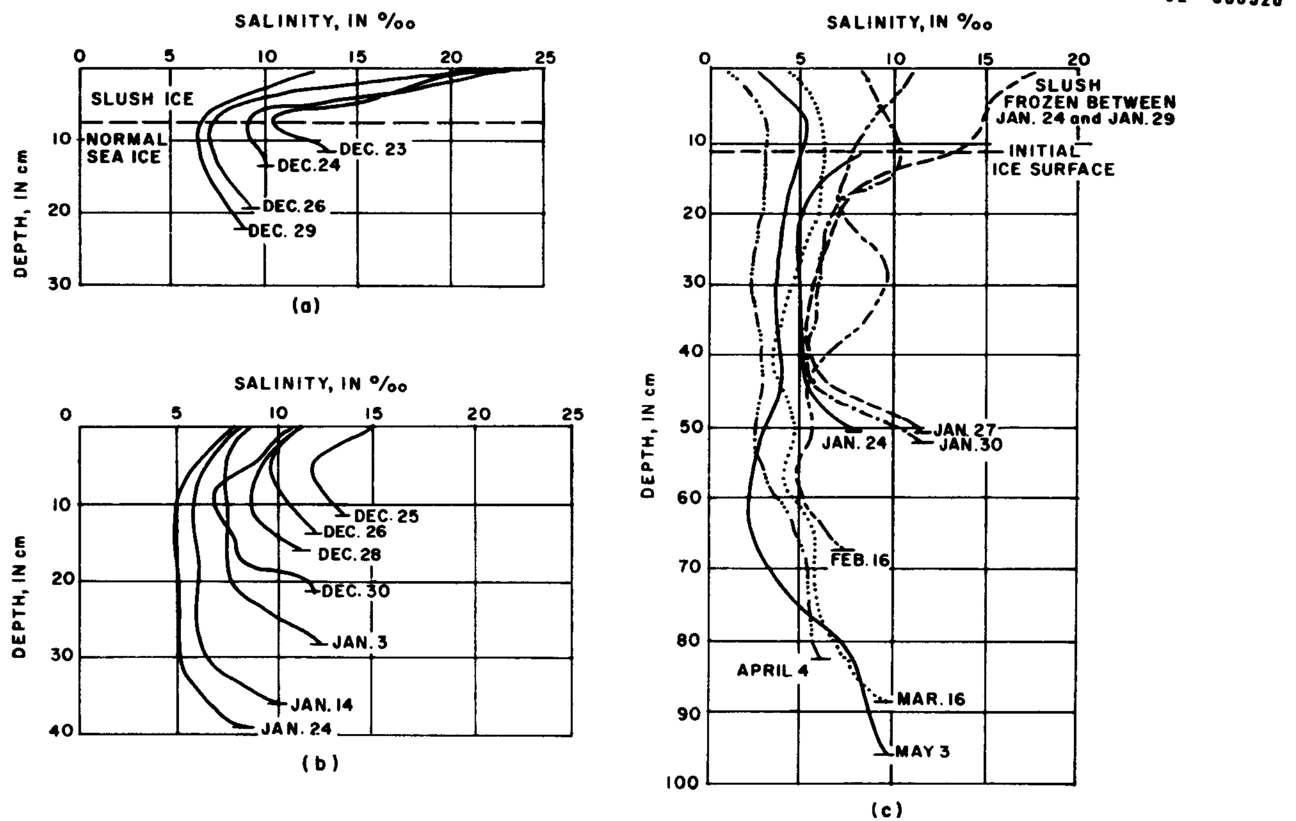

Figure 3-7 SALINITY PROFILES IN SEA-ICE

slush. The very high surface salinity of the slush ice layer is apparent. The reduced salinity of the more slowly growing bottom layers of ice is also noticeable. Figure 3-7b shows the first month of drainage from a specimen of sheet ice. The initial salinity at the surface of the sheet ice is much less than that of the frozen slush, but the drainage rates appear to be about the same. In some cases, the lack of vertical orientation in the slush ice brine cells will lead to appreciably slower drainage rates in the slush ice. Figure 3-7c shows the salinity profiles and drainage for the first five months in the life of a specimen of sea-ice covered with slush-ice. The salinity profile prior to slush formation is considerably lower than the profile immediately after slush has formed and frozen. The downward drainage of brine is quite apparent in these curves. After less than five months of drainage, the top 10 cm of ice shows an average salinity of approximately 2 0/00. The upward migration of brine in the early summer becomes apparent in the May profile, even though the underside of the ice is still growing.

4. ELECTRICAL PROPERTIES OF ICE

4.1 Theoretical Considerations

Since sea-ice is essentially a matrix of pure ice containing vertical cylindrical inclusions of brine or deposited salts, its electrical properties are best understood by considering first the electrical properties of the pure ice matrix, and then considering the secondary influence of the brine and salt inclusions upon these properties.

4.1.1 Characteristics of Pure Ice

Chemically pure ice has a D-C conductivity of about 10^{-7} mho/m [Auty and Cole, 1952]. It can be classified as a "protonic semiconductor" since, according to Frank [1957], the conduction mechanism involves quantum mechanical tunnelling of hydrogen ions between lattice defects. These mechanical defects in the structure will vary widely from sample to sample, depending upon the details of the freezing process. Since the effect is so small, it will not be considered further here.

Although chemically pure ice is a very poor conductor, it is still a lossy dielectric. This is because the water molecules, having a permanent dipole moment, introduce "relaxation absorption" over a range of frequencies between 10 c/s and 100 kc/s.

a) Effect of Frequency

In an ideal capacitor containing a perfect loss-free dielectric material, the displacement current would lead the applied voltage by 90° and there would be no loss of electrical energy in the dielectric. The capacitance would be given by the relation

$$C_p = \epsilon' \epsilon_o A/d \tag{3}$$

where

C_p = capacitance of perfect capacitor, expressed typically in farads,

A = area of capacitor plates in m^2,

d = capacitor plate separation, in m,

ϵ_o = permittivity of free space (8.85×10^{-12} farads/m)

ϵ' = relative permittivity of the loss-free dielectric (the symbol $\epsilon' = \epsilon/\epsilon_o$ is used in place of the more familiar $K = \epsilon/\epsilon_o$ because of its common usage in the fundamental theories of dielectrics).

If dielectric materials containing polar molecules are used, the capacitor current leads the applied voltage by less than 90° and dielectric losses occur. If the capacitor is fed with a sinusoidal voltage V, of frequency ω, the quadrature component of current will be $V \omega \epsilon' \epsilon_o A/d$ and the component of current in phase with the voltage can be expressed as $V \omega \epsilon'' \epsilon_o A/d$

where ϵ'' = dielectric loss factor

ϵ' and ϵ'' can then be used to express a complex permittivity $\bar{\epsilon}$

where $$\bar{\epsilon} = \epsilon' - j\epsilon'' \tag{4}$$

The loss current $V \omega \epsilon'' \epsilon_o A/d$ may be reinterpreted in terms of an effective parallel conductivity σ. Thus, setting $V \omega \epsilon'' \epsilon_o A/d = V \sigma A/d$

$$\begin{aligned} \sigma &= \omega \epsilon'' \epsilon_o \\ &= \omega \epsilon' \epsilon_o \tan \delta \end{aligned} \tag{5}$$

where δ is the loss angle.

Thus an alternate expression for the complex permittivity is:

$$\bar{\epsilon} = \epsilon' - j \frac{\sigma}{\omega \epsilon_o} \tag{6}$$

An alternate, and possibly more familiar representation expresses the in-phase and quadrature components of current in terms of a real conductivity σ, an imaginary conductivity σ' and a complex conductivity $\bar{\sigma}$.

Thus, the in-phase current may be expressed as $V \sigma A/d$.

The quadrature component of current, $V \omega \epsilon' \epsilon_o A/d$ is expressible in the form $V \sigma' A/d$ if

$$\begin{aligned} \sigma' &= \omega \epsilon' \epsilon_o \\ &= \omega \epsilon \end{aligned} \tag{7}$$

where ϵ = permittivity of the dielectric in farads/m.

Thus

$$\begin{aligned} \overline{\sigma} &= \sigma + j\sigma' \\ \overline{\sigma} &= \sigma + j\omega\epsilon \end{aligned} \tag{8}$$

The 'relaxation absorption' losses associated with these polar molecules occur in the following way. Under the influence of an applied oscillating electric field, the orientation polarization which occurs enhances the capacitance. As the frequency is raised, the dipole orientation is delayed, the polarization and hence ϵ' decreases, and the dielectric loss factor, ϵ'', passes through a maximum. The frequency at which this 'relaxation absorption' loss factor becomes a maximum is known as the relaxation frequency, f_r. The reciprocal of this frequency, called the relaxation time τ, characterizes the rate of buildup or decay of the polarization when the electric field is suddenly changed. Of course, if other loss factors beside 'relaxation absorption' are present, the total ϵ'' may reach a maximum at some frequency other than f_r.

If the material contains dipoles with a single relaxation time, the frequency dependence of ϵ' and ϵ'' can be described by the Debye equations

$$\epsilon' = \epsilon'_\infty + \frac{\epsilon'_s - \epsilon'_\infty}{1 + \omega^2 \tau^2} \tag{9}$$

$$\epsilon'' = (\epsilon'_s - \epsilon'_\infty) \frac{\omega \tau}{1 + \omega^2 \tau^2} \tag{10}$$

where ϵ'_s = static permittivity

ϵ'_∞ = high frequency permittivity

If an Argand diagram is made with ϵ' as real abscissa and ϵ'' as imaginary ordinate, the variation of ϵ' and ϵ'' with frequency describes a semicircle in the complex plane with center on the ϵ' axis at $\epsilon'_\infty + \frac{\epsilon'_s - \epsilon'_\infty}{2}$ and radius $\frac{\epsilon'_s - \epsilon'_\infty}{2}$. Such a plot is known as a Cole plot and can be used to identify samples which possess only one relaxation frequency.

Furthermore, a substitution of equations (9) and (10) into equation (4) yields the following dispersion relation:

$$\bar{\epsilon} = \epsilon'_\infty + \frac{\epsilon'_s - \epsilon'_\infty}{1 + j\omega\tau} \tag{11}$$

$$= \epsilon'_\infty + \frac{(\epsilon'_s - \epsilon'_\infty)}{1 + j\, f/f_r} \tag{12}$$

where f_r = relaxation frequency.

Very pure polycrystalline ice is a polar substance and since it fits a Cole plot, it must have a single relaxation frequency. Very reliable measurements of the complex conductivity and permittivity of pure polycrystalline ice have been made by Auty and Cole [1952], and the form of the dispersion is shown in Figures 4-1 and 4-2.

b) Effect of Temperature

Dielectric losses due to the 'relaxation absorption' by permanent dipoles are temperature dependent. The relaxation time is influenced by the thermal agitation of the dipoles and on the basis of Maxwell-Boltzmann statistics, should obey the following relationship.

$$\tau = C_1 e^{C_2/kT} \tag{13}$$

where C_1, C_2 are experimentally measured constants,

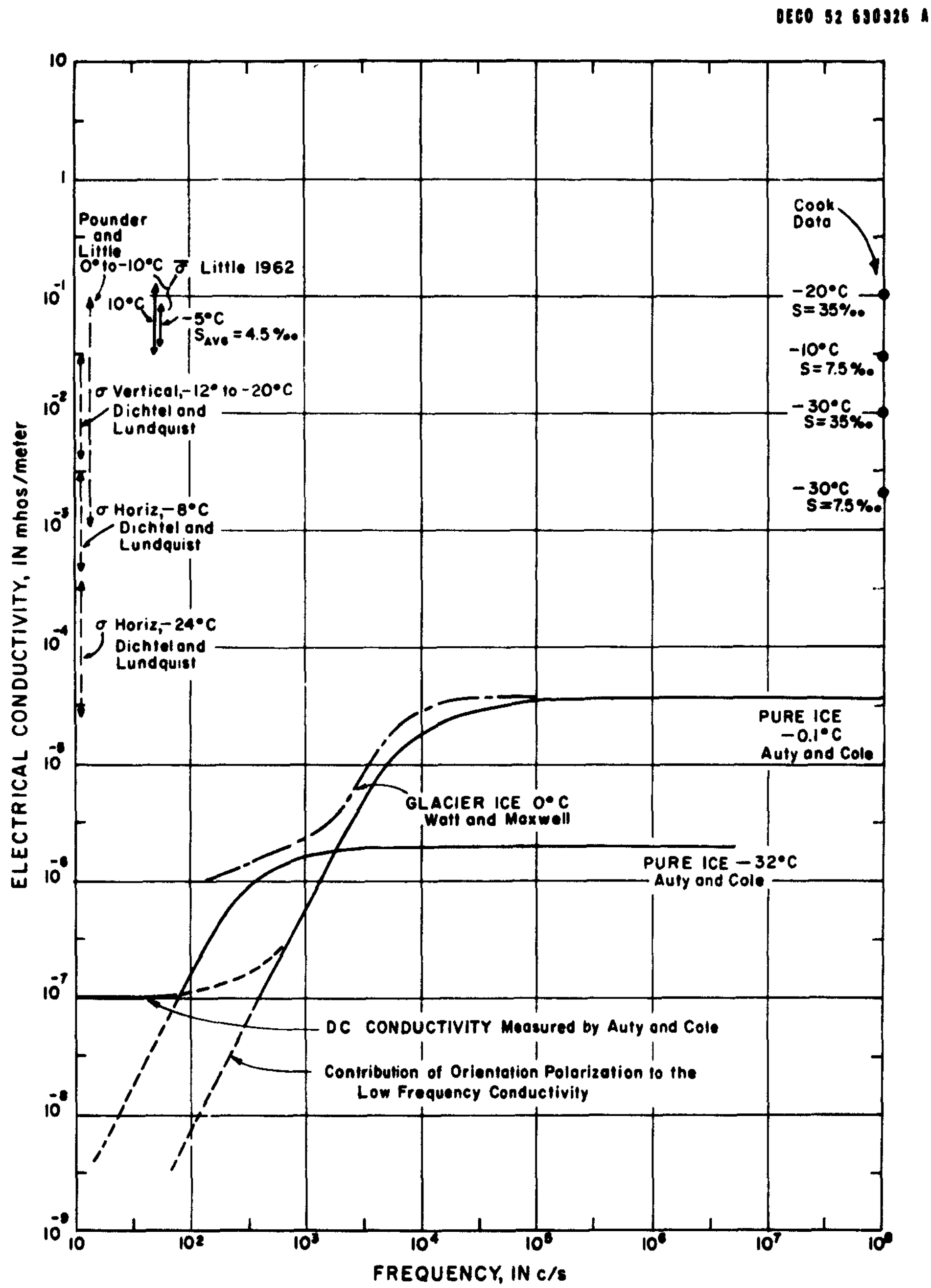

Figure 4-1 CONDUCTIVITY VS FREQUENCY FOR PURE ICE, GLACIAL ICE AND SEA-ICE

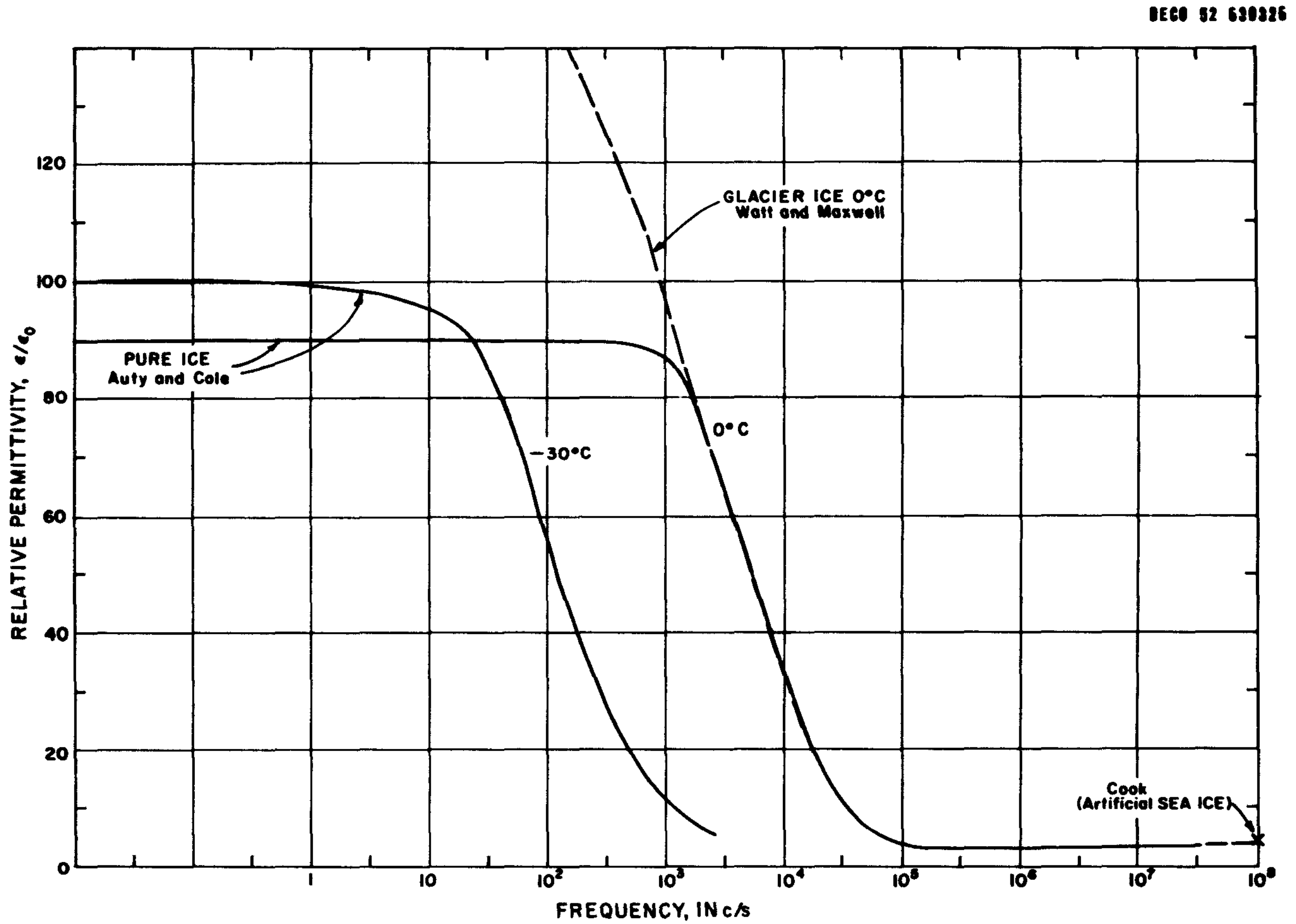

Figure 4-2 RELATIVE PERMITTIVITY VS FREQUENCY FOR PURE ICE, GLACIAL ICE AND SEA-ICE

k = Boltzmann's constant

T = absolute temperature in degrees K.

This is confirmed by experiment, down to about -40° C, and as the curves of Figures 4-1 and 4-2 show, the region of dispersion of ϵ'_s shifts to lower frequencies at lower temperatures.

As the temperature is reduced the degree of polarization should increase due to the decreased thermal agitation of the dipoles. Thus ϵ'_s should increase and the Cole plot should have a larger diameter. This is also found to be the case for pure polycrystalline ice and shows in Figures 4-1 and 4-2.

c) Effects of Crystal Size and Orientation

Humbel, Jona and Scherrer [1953] have measured both polycrystalline ice, and single ice crystals. Their results show that the Cole plot for a single crystal of ice is still a semi-circle, but larger than that for polycrystalline ice of the same temperature. In fact, the generalization can be made that, the more fractured the ice, the smaller will be the diameter of the Cole plot, although ϵ'_∞ remains unchanged. Single crystal studies have also revealed a marked anisotropy in the dielectric constant. Just below the freezing point the value of ϵ' measured parallel to the c-axis of the crystal is some 15 - 30% higher than the value perpendicular to this axis. The degree of anisotropy decreases with decreasing temperature. At 10 kc/s it disappears around -25° C but at 50 c/s it persists to about -60° C.

4.1.2 Effect of Impurities on Characteristics of Pure Ice

There are three main classifications of impurities in ice: those existing integrally in the crystal lattice; those existing in crystal voids or along grain boundaries as crystallized salts; and those existing in the same voids but as ions in solution. The first two classes will, in general, produce relaxation absorption as described by Debye, but with relaxation time or times different from that of pure ice. The last form of impurity will give rise to 'interfacial' or Maxwell-Wagner [1914] polarization. This last type of polarization can

produce an absorption and a dispersion very similar to that produced by dipole orientation if the cavities are approximately spherical. Otherwise, the absorption may be quite different. In all three classes of impurities the Cole plot of ϵ'' vs ϵ' should show a marked departure from a semi-circle at low frequencies. This is caused in part by the existence of an appreciable D-C conductivity associated with the impurities. In relaxation absorption, ϵ'' is proportional to ω in the limit of low frequencies. Hence $\sigma = \omega \epsilon_o \epsilon''$ is proportional to ω^2 as ω approaches zero. However, if there is a finite DC conductivity, σ will approach σ_{DC} rather than zero. This has been demonstrated experimentally in glacier ice by Watt and Maxwell [1960]. They show a σ varying as $\omega^{1/3}$ down to about 100 c/s. Presumably, below this frequency, the conductivity curve would level out to the D-C value. Conversely if this conductivity were used to express an equivalent $\epsilon'' = \sigma/\omega\epsilon_o$, ϵ'' would increase without limit as ω approaches zero in marked distinction to the normal Cole plot where ϵ'' approaches zero as ω approaches zero.

a) Effect of Impurities Integral to the Crystal Lattice

Several workers, Brill, Brill and Camp [1957] and Granicher et al, [1957] have studied the properties of 'mixed crystals' of ice and impurities. In these 'mixed crystals' the impurity molecule replaces a water molecule but uses the same bonds. Thus the overall structure is unchanged except for small variations in atom sizes at the impurity sites. Typical impurities which have been studied are HCl, NH_4Cl, HF and NH_4F. Since sea water contains appreciable concentrations of H^+, F^-, and Cl^- ions, it is entirely possible that these could be incorporated into the growing crystal lattice of sea-ice, even though almost all other ions would be rejected into adjacent brine cells. At present there is no experimental confirmation of this conjecture.

Brill and Camp [1957] have shown that these 'mixed crystals' have electrical properties obeying a Cole plot of sorts. Values of ϵ' and ϵ'' still yield points lying on a circular arc, but the centre of this arc is displaced

below the ϵ' axis. Such a curve is indicative of a distribution of relaxation frequencies among the water molecules in the neighborhood of the structure disturbing impurity sites. According to Böttcher [1952], an average relaxation time τ can still be obtained from any point P on the circular arc from the relation

$$\frac{v_1}{u_1} = (\omega_1 \tau)^{1-h} \tag{14}$$

where

ω_1 = angular frequency corresponding to the point P,

u_1 = distance from P to ϵ'_∞

v_1 = distance from P to ϵ'_s

$1 - h$ = circular arc, in radians, subtended by the ϵ' axis.

The studies of Brill and Camp [1957] show relaxation frequencies which decrease with decreasing temperature and which, for a given temperature are maximum for an optimum impurity concentration around .1 to 1%. Table I summarizes these frequencies as they are obtained from Brill's [1957] Cole plots.

TABLE I

Approximate Average Relaxation Frequencies for Mixed Ice Crystals

Impurity Concentration (%)	T = -50°C	T = -25°C
.002	0.3 kc/s	0.5 kc/s @-35°C
.02	2.5 kc/s	5.3 kc/s
.15	10.0 kc/s	40.0 kc/s
1.0	16.0 kc/s	---
10.0	5.0 kc/s	10 kc/s @-35°C

b) Effect of Crystallized Impurities in Voids and Grain Boundaries

From Figure 3-3 it is apparent that the major crystallized salts found in sea-ice are $MgCl_2 \cdot 12H_2O$, $NaCl \cdot 2H_2O$, $Na_2SO4 \cdot 10H_2O$, and to a lesser extent, KCl, $MgCl_2 \cdot 8H_2O$ and $CaCo_3 \cdot 6H_2O$. Dryden and Meakins [1957] report no dielectric absorption in pure KCl and $NaCl$ other than that arising from the presence of D-C conductivity. However, in the presence of divalent impurities, such as Mg, Ca, Sr, and Ba, two dispersion and absorption peaks were observed with very low relaxation frequencies. This absorption occurs because the positive impurity ions form an effective dipole with the alkali metal ion vacancy. The lower peak in each salt exhibited a Debye type absorption, with a relaxation frequency of approximately 2 c/s at -10°C for $NaCl$ (Ca impurity) and approximately 8 c/s at -10°C for KCl (Ca impurity).

The second absorption peak in these salts has a relaxation frequency 100 times greater than that of the lower peak. It does not appear until the impurity concentration exceeds .075 mole%. This absorption peak is broader than a typical Debye absorption peak. The mechanism of its existence is not understood. Since the four ions discussed here, (Cl^-, Na^+, K^+, Ca^{++}) are among the six most abundant ions present in sea water, this absorption factor should be present in sea ice.

The presence of water of hydration in crystallized salts must be considered since the water molecules are polar. However, very few inorganic hydrates exhibit dielectric absorption. Presumably therefore, the water molecules are arranged in such a way as to have a net dipole moment of zero. Nothing has been found in the literature to indicate any dielectric absorption by the salts which are known to be present in sea ice.

c) Effects of ions in Solution in Voids and Grain Boundaries

Previously, the polarization mechanisms discussed have involved bound charges. However, if charges are free to migrate, such as ions in solution, there will be a piling up of space charges in the volume, and surface

charges at the boundary between void and ice. This results in 'interfacial polarization' as discussed in the work of Maxwell [1892] and Wagner [1924].

VonHippel [1954] has shown that a capacitor containing any number of parallel layers of conductivity σ_1, and permittivity $\epsilon'_1 \epsilon_o$, separated by parallel layers of conductivity σ_2 and permittivity $\epsilon'_2 \epsilon_o$ can be expressed as a simple two-layer capacitor in which the two types of dielectric are concentrated into two homogeneous parallel layers of appropriate thicknesses d_1 and d_2.

The two layer capacitor will have a capacitance

$$\epsilon' \epsilon_o A/d$$

where

ϵ' = effective relative permittivity of the entire medium,

$d = d_1 + d_2$

A = area of capacitor plates.

The equivalent circuit of the two-layer capacitor is expressed in terms of the equivalent parallel resistance R, and capacitance C of the individual layers. Using subscripts 1 and 2 to denote layers 1 and 2, the parallel combination of R_1 and C_1 is in series with the parallel combination of R_2 and C_2.

The relaxation time of this two-layer capacitor is given by

$$\tau = \frac{(\epsilon'_1 d_2 + \epsilon'_2 d_1) \epsilon_o}{\sigma_1 d_2 + \sigma_2 d_1} \tag{16}$$

If the relaxation times of the two media are expressed as τ_1 and τ_2, the effective relative permittivity of the entire capacitor is given by

$$\epsilon' = \epsilon'_\infty (1 + \frac{K}{\omega^2 \tau^2}) \tag{17}$$

where

$$K = \frac{\epsilon'_s - \epsilon'_\infty}{\epsilon'_\infty}$$

$$\epsilon'_s = \frac{\tau_1 + \tau_2 - \tau}{\epsilon_o A/d\,(R_1 + R_2)}$$

$$\epsilon'_\infty = \frac{\tau_1 \tau_2}{\epsilon_o A/d\,(R_1 + R_2)\,\tau}$$

The effective dissipation factor ϵ'' becomes

$$\epsilon'' = \epsilon'_\infty \left(\frac{\tau}{\omega \tau_1 \tau_2} + \frac{K\omega\tau}{1 + \omega^2 \tau^2}\right) \qquad (18)$$

Thus as far as ϵ' is concerned the dispersion due to interfacial polarization is indistinguishable from a Debye type dispersion. However, in the case of ϵ'', in addition to a Debye type term, there is the term $\frac{\epsilon'_\infty \tau}{\omega \tau_1 \tau_2}$ corresponding to a conductivity $\frac{\epsilon'_\infty \epsilon_o \tau}{\tau_1 \tau_2}$ due to the series resistor $R_1 + R_2$. If now medium 2 is subdivided, and dispersed throughout medium 1, the dielectric properties remain unchanged as long as the shape and orientation of the subdivisions are the same as those of the original layer. However, if the shape or orientation of the subdivisions is altered, the frequency response will then be changed. Sillars [1937] has shown that if medium 2 is distributed throughout medium 1 in the shape of spheres or ellipsoids, the loss factor ϵ'' will show a single peaked frequency response with ϵ''_s and ϵ''_∞ both approaching zero. The single peaked frequency response of ϵ'' becomes broader and shifted toward lower frequencies as the eccentricity of the ellipsoids is increased in the direction of the applied field. If the eccentricity of the ellipsoids is increased without limit, medium 2 is distributed as cylinders between the capacitor plates. In this case ϵ'' increases without limit as the frequency approaches zero.

For the case of long needle-shaped cavities parallel to the field with axial ratio a/b, a > b, Sillars has shown that

$$\tau = \frac{\epsilon'_1}{4\pi\,\sigma_2}\,(a/b)^2\,\frac{1}{\mathrm{Log}\,(2\,a/b - 1)} \tag{19}$$

regardless of the value of ϵ'_2 .* Thus, for sea ice with long vertical brine cells, the actual distribution of axial ratios a/b implies a distribution of relaxation times τ. Thus, the dispersion in ϵ' and ϵ'' will be broader than that implied for the single relaxation times of equations (17) and (18).

4.2 Observed Characteristics

There are very few data available on the electrical characteristics of sea-ice. In the light of the complexity of sea-ice discussed in the preceding sections, this lack of data is to be expected. The few data which are available show a large amount of scatter. Again this is to be expected since in many of the measurements, crystal orientations, and differential drainage of brine types were not considered.

4.2.1 Conductivity, including Effects of Temperature, Salinity, Frequency, Orientation and Age.

The electrical conductivity, which determines the magnitude of the in-phase component of current resulting from an applied voltage may be

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* This insensitivity to the value of ϵ'_2 is fortunate because in practice, it is extremely difficult to measure the dielectric constant of solutions of electrolytes. This is because of the masking effect of the large conductivities of these solutions. The $\sigma/\omega\epsilon_0$ term associated with the A-C conductivity plus the ϵ'' term associated with dielectric losses combine to give a loss tangent so large that measurements of ϵ' are extremely difficult. However, recent measurements by Little [1958] indicate a drop in ϵ' from that of pure water. The decrease is inversely related to the electrolyte concentration and the rate of decrease decreases slightly with increasing concentration. At a concentration of 1 mole/litre the decrease in ϵ' is about 10%.

expressed as

$$\sigma = \sigma_o + \sum \epsilon''_i \epsilon_o \omega \tag{20}$$

where σ_o represents any DC conductivity and ϵ''_i represents the contribution of a particular dielectric loss mechanism.

In the case of sea-ice, there will be in addition to the DC conductivity of pure ice which is in the order of 10^{-7} mho/m, an additional (but at present unknown) DC conductivity associated with the brine cells. There will also be an ϵ'' which decreases with increasing frequency. This term will arise from interfacial polarization between the sea-ice crystals and should thus be larger for σ measured horizontally than for σ measured vertically. In addition, there will be an ϵ'' having a peaked response around a particular relaxation frequency f_r for each of the Debye polarization mechanisms discussed in sections 4.1.1 and 4.1.2. These ϵ'''s will give a contribution to the conductivity which approaches zero at low frequency and approaches $\frac{\epsilon_o(\epsilon'_s - \epsilon'_\infty)}{\tau}$ at high frequencies. These relaxation frequencies, of course, are all temperature dependent, and the amount of absorption associated with each will also be temperature dependent because of the changing amounts of ice, brine, and salts present at different temperatures.

There is insufficient detailed knowledge at present to make an accurate calculation of anticipated values of σ, but in a general way, the conductivity will go from some DC value, increase through a region of overlapping dispersions (10 c/s to 60 kc/s approx.), and finally level out to a larger high frequency value, broken only by resonance absorptions in the microwave and optical regions of the spectrum.

Figure 4-1 shows a superposition of conductivity data obtained by several workers. The pure ice values of Auty and Cole for polycrystalline ice show a single region of dispersion, a constant high frequency value, and the expected decrease in relaxation frequency with temperature. The data

of Watt and Maxwell for glacier ice at 0° C show good high frequency agreement with the pure ice data. They show a low frequency departure associated with DC conductivity introduced by ice impurities. Interfacial polarization losses caused by ice crystal boundaries undoubtedly contribute here also. DC data for sea-ice have been obtained by Pounder and Little [1959], by Dichtel and Lundquist [1951], and by Voegtli [1961]. Those by Pounder and Little, and by Voegtli were in situ measurements using a four-terminal Wenner array. Those by Dichtel and Lundquist were four-electrode measurements made on samples cut from sea-ice. None of the measurements were correlated with salinity determinations, although in the case of the Dichtel and Lundquist data, the average salinity may be estimated as about 5 0/00. A trend of decreasing conductivity with decreasing temperature may be inferred from the Dichtel and Lundquist data, but it is obvious from a comparison with the Pounder and Little data, that the salinity must be established with much more certainty before this can be considered as established.

The only AC data available are by Little [1962] on sea-ice at approximately 50 c/s and by Cook, on artificial sea-ice at 100 mc/s. Little's data include only partial information on temperature and salinity. Hence no positive correlation between temperature, salinity and conductivity can be achieved. Cook's [1960] data include precise values of temperature and salinity, but by the author's own admission, the grain size and orientation were completely different from conditions found in natural sea-ice. However, the temperature and salinity dependence appear to vary in the correct direction and the magnitude of the conductivity compares favorably with the DC values.

4.2.2 Relative Permittivity, including Effects of Temperature, Salinity, Frequency Orientation, and Age.

Data on relative permittivity of sea-ice are even more sparse than those for electrical conductivity. Except for 100 mc/s measurements on artificial sea-ice by Cook, no other measurements have been located. Cook lists values of relative permittivity, ϵ', ranging from 3.1 to 4.3, with no clear

cut correlation with temperature or salinity. His value is shown on Figure 13 along with pure ice values from Auty and Cole and glacial ice values from Watt and Maxwell.

On the basis of the information in sections 4. 1. 1 and 4. 1. 2 an estimate can be made of the expected trends in sea-ice. Above the dispersion region of frequency, ϵ' will behave essentially the same as glacial ice or pure ice. This is because all the polarization mechanisms considered possible in sea ice involve relaxation frequencies less than that of pure ice. The increase in ϵ' observed in polycrystalline stubstances at low frequencies is primarily due to interfacial polarization and is often so large that it masks all other low frequency polarization effects. Since in general, sea-ice would tend to be less crystalline than the upper layers of a glacier, particularly if the sea-ice were at all old, the relative permittivity for sea ice at low frequencies can be expected to lie between the Watt and Maxwell and the Auty and Cole curves.

5. TOPOGRAPHICAL PROPERTIES OF SEA ICE

5.1 General Discussion

The Polar Sea with its adjacent seas, the western portion of the Norwegian Sea, Baffin Bay, and the western portion of the Labrador Sea are covered by sea-ice during the greater part of the year. Large, flat ice floes are rare as the surface is generally hummocked. Pressure ridges rising up to five or six meters above the general level of the ice are frequently found. This rugged appearance of the pack ice is ascribed to wind action and the restricted freedom of motion of the ice imposed by land barriers on all sides.

The ice of the northern seas may be grouped into two major categories, namely, winter ice, or ice of one year's growth or less, and polar ice, or ice of more than one year's growth. Winter ice forms in the open water areas (polynyas, leads and cracks) that are scattered throughout the polar pack and often becomes churned into fragments by strong winds and water currents. Winter ice that forms along the coast-line and extends seaward is known as winter fast ice and in shallow areas where islands are close together it blankets wide areas and forms a continuous bridge between the individual islets and islands. Although the local severity of the winter determines the rate of growth of winter ice, it averages 6 to 8 feet in one season.

The perennial ice that exists in the Arctic Ocean and bordering seas is known as Polar ice. The average thickness of Polar ice is normally about 10-13 feet, but decreases to 6-10 feet by the end of summer. About 20 inches of the top surface of Polar ice is lost by ablation each year but is compensated for by a similar accumulation of new ice on the undersurface.

Except for the limits of sea-ice, shown in Figure 1-1, little is known about its geographic distribution because the march of civilization has generally avoided areas where sea-ice exists. Until the recent cruises of atomic submarines under the pack ice, information was usually subjective and related to a ship's ability to navigate or avoid ice infested waters.

5.2 Sea Ice Profile Characteristics and Distribution

The capability of submarines to navigate under sea-ice has opened new operational areas to the submariner. However, he requires new knowledge regarding the Arctic waters and the ice under which he must navigate if he is to extend his operations into this new environment safely and effectively. Lyon [1961] gives a very graphic picture of the bottom profile of sea-ice:

> "To the submariner, this ice covering the sea appears to be a canopy over his ship. During summer, the canopy is a drifting fragmented collection of melting pieces of ice which have all possible sizes, shapes, and thicknesses: For example, large flat areas 5-to-12 feet thick, or old pressure ridges where the ice sheet had broken and stacked in great, jumbled heaps to a thickness of 30 feet or more, possibly to 130 feet. Similarly, the open water spaces between ice floes have all sizes and shapes; total coverage of water is, perhaps, 5 per cent. Many open water spaces (lakes) are sufficiently large for a submarine to surface without contacting ice. During winter, the old summer ice is cemented together by new sea ice into a contiguous ice canopy. Under wind stress, zones of compression and tension develop within the canopy producing pressure ridges in compression and great cracks, or leads, in tension. These leads are of particular interest to the submariner because open water is exposed, which under winter ambient air temperatures will be quickly covered with new sea ice. The thin spots, thickness three feet or less, that form in the canopy are called skylights, because of the distinctive appearance of the sunlight transmitted through the thin ice."

At a temperature of -40°C, 1 inch of new ice may be expected to form within a few hours, about 1 foot within a week and 3 feet within a month. Although sea-ice growth and heat budget studies are still in progress, it is known that growth rate depends upon many factors including water temperature, salinity, air temperature, wind, cloud cover and snow fall.

Knowledge of the character of the sea-ice canopy was greatly extended when the Nautilus recorded a continuous profile of its undersurface during the transpolar cruise in August, 1958. A portion of the track of this cruise is shown in Figure 5-1. Recordings were made from soundings by a narrow-beamed, upward-looking sonar operating on 150 kc/s. Since insufficient open water is available as a reference for under ice draft measurements, the Nautilus used the hydrostatic pressure at the vessel to compute the vertical distance to the sea surface, knowing the density of the sea water and the gravitational constant. Automatic corrections for changes in the vessel's depth were made through a servomechanism between the pressure sensing device and the echosounder. Thus the open-water surface is always set at the top zero line of the recording paper and the ice draft is read directly as depth beneath the zero reference line. Three samples of the ice canopy profile as recorded by Lyon [1961] on the Nautilus are shown in Figure 5-2. The horizontal and vertical scales are in feet and, as will be noted, the horizontal scale has been compressed by a factor of approximately 60. Since such extreme compression is apt to create a misconception regarding the true profile characteristics of the ice canopy, a portion of the middle recording has been redrawn in Figure 5-3 to a compression factor of 6. The underside of the ice shows excursions in depth averaging 10 to 15 feet, occasional large peaks as deep as 50 feet, and maximum excursions from 100 to 150 feet in depth. Top profiles will show variations from 1/3 to 1/7 as large.

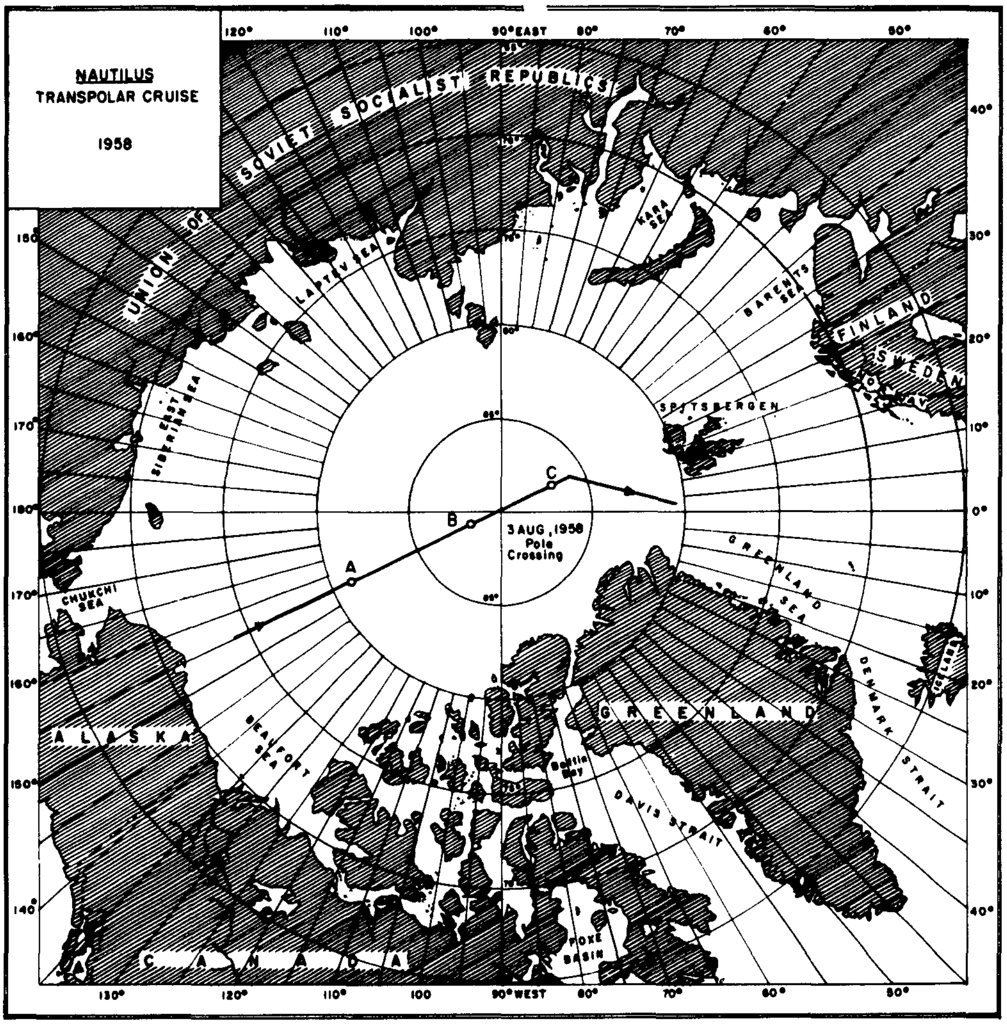

Figure 5-1 TRACK OF NAUTILUS, 1958 TRANSPOLAR CRUISE

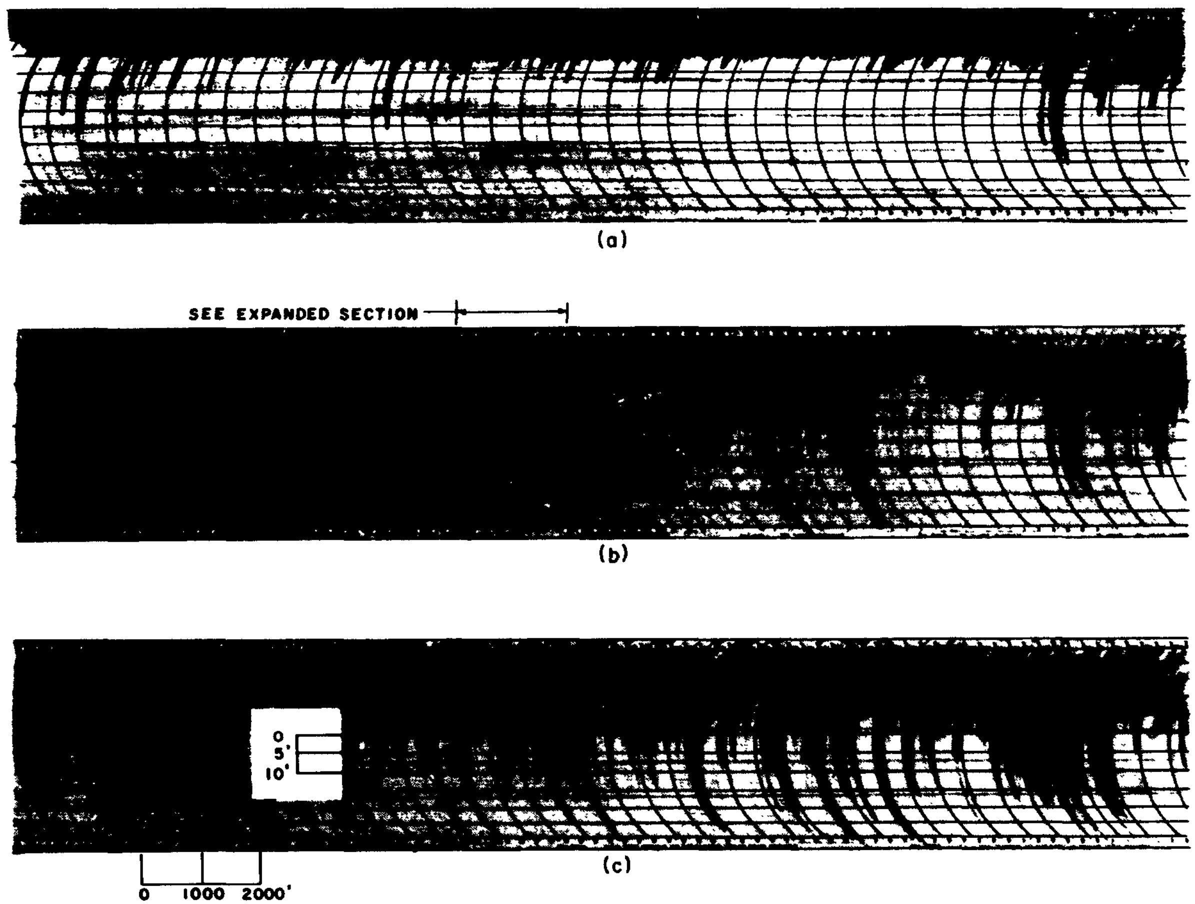

Figure 5-2 SAMPLE ECHOSOUNDER RECORDS OF ICE CANOPY NAUTILUS 1958 TRANSPOLAR CRUISE

DECO 52 630326 P

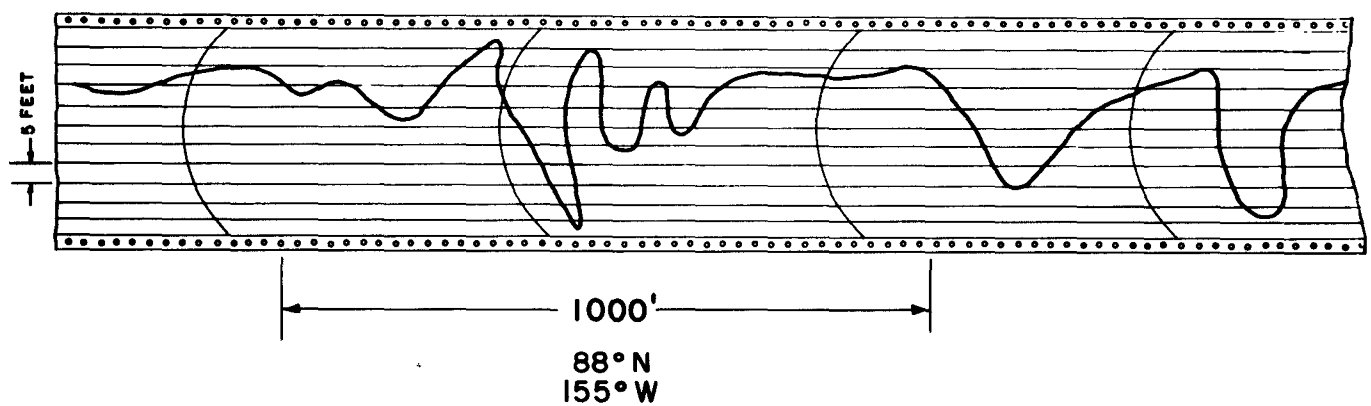

Figure 5-3 SECTION OF ECHOSOUNDER RECORD, COMPRESSION FACTOR 6

The distribution of ice and open water along the track is shown on the graphs of Figure 5-4. The number of open water spaces per 10 nautical miles is plotted against latitude along the transit course in the upper graph of Figure 5-4. The line-connected points give the number of spaces 100 feet or greater in length, those 300 feet or greater by vertical lines, and those 1000 feet or greater by vertical bars. The average draft of the ice in feet per 10 nautical mile increment is plotted in the lower graph. It will be noted that there is a progressive, general change in character of the ice canopy from the Pacific to the Atlantic side of the Arctic Ocean, the number of pressure ridges being much greater on the Atlantic side.

Ice thickness measurements have been made in the Arctic areas by numerous investigators since Nansen's historic transit of the Arctic Ocean in the Fram between 1893 and 1896. Considerable information was added by the drift of the Soviet manned ice station North Pole 1, initiated near the north geographic pole in 1937. The Fram began her drift at 78.6° N, 139.1° E in November of 1894 and arrived at 83.2° N, 10.3° E in June, 1896. The North Pole 1 drifted between 82.8° N, 7.0° W and 70.7° N, 19.3° W between November 1937 and February 1938. The variations in ice thickness with time as measured by these stations is plotted in Figure 5-5. This figure also shows a theoretical curve as computed by Zubov and the results of a series of measurements made by the US-IGY station A. This station drifted from 80.9° N, 159.5° W to 84.1° N, 149.7° W between June 1957 and June 1958.

5.2.1 Relative Thickness of Polar Sea-Ice Above and Below the Water Level

Figure 5-6 shows the cross section of a typical Polar ice floe. It will be noted that the floe consists of a relatively level part and a deformed part. The symbols used to represent the various thicknesses in Figure 5-6 and Table II are as follows:

i = Total thickness of ice

h = Height of top of ice above water level

z = Depth of bottom of ice below water level

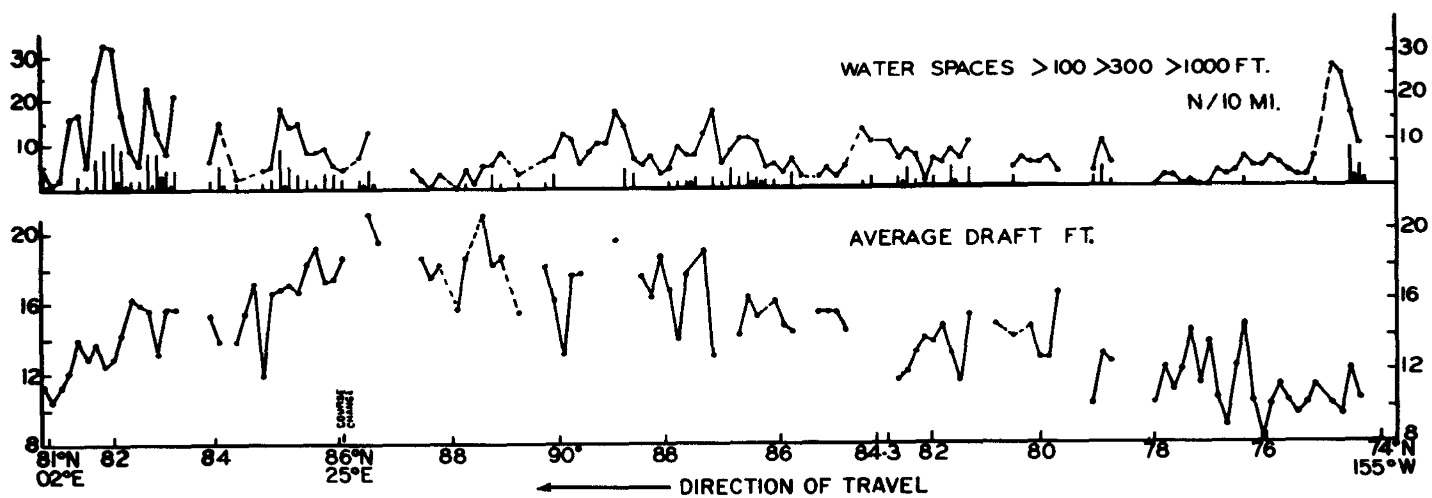

Figure 5-4 POLYNA DISTRIBUTION, AND AVERAGE DRAFT OF ICE
NAUTILUS 1958 TRANSPOLAR CRUISE

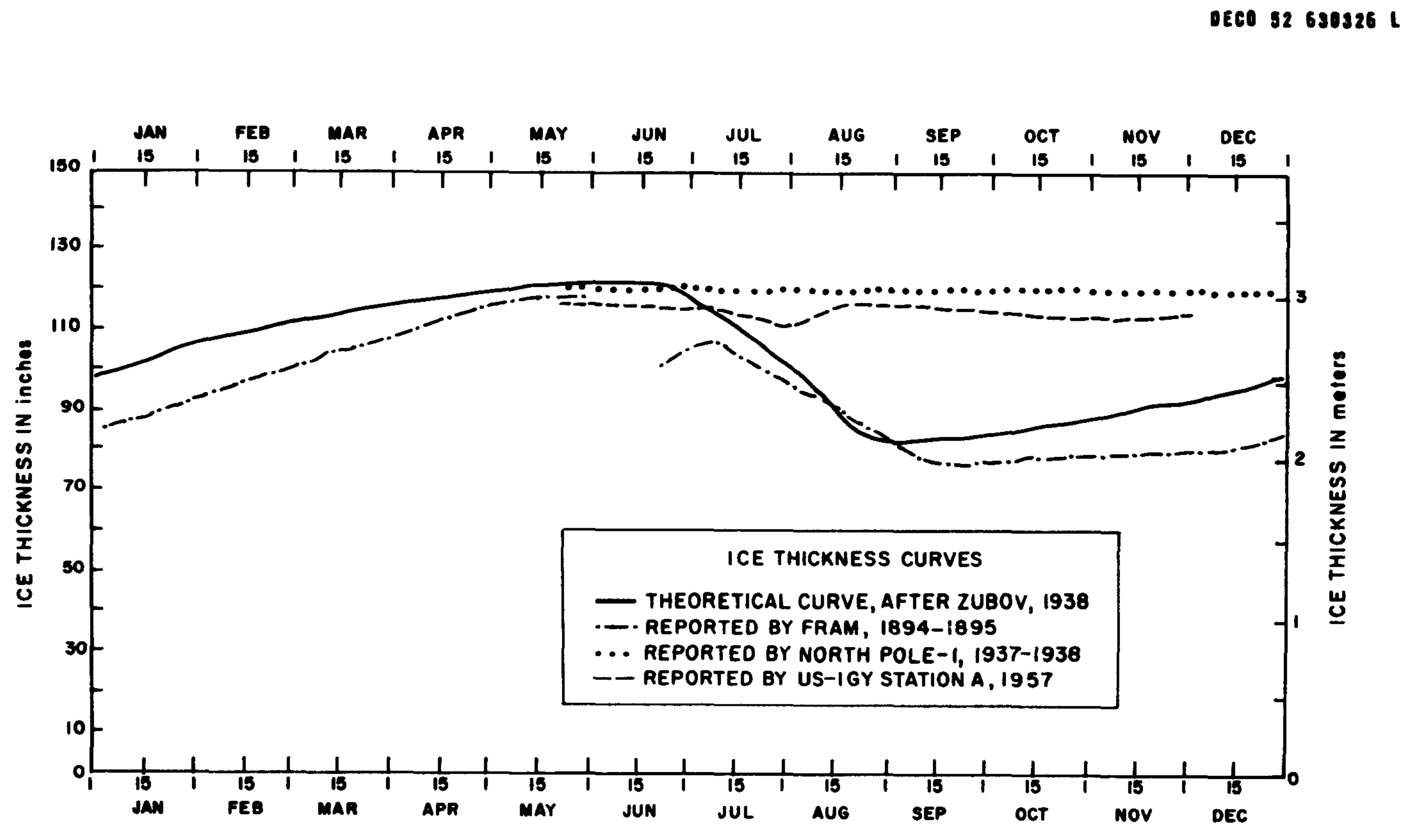

Figure 5-5 SEASONAL VARIATIONS IN ICE THICKNESS

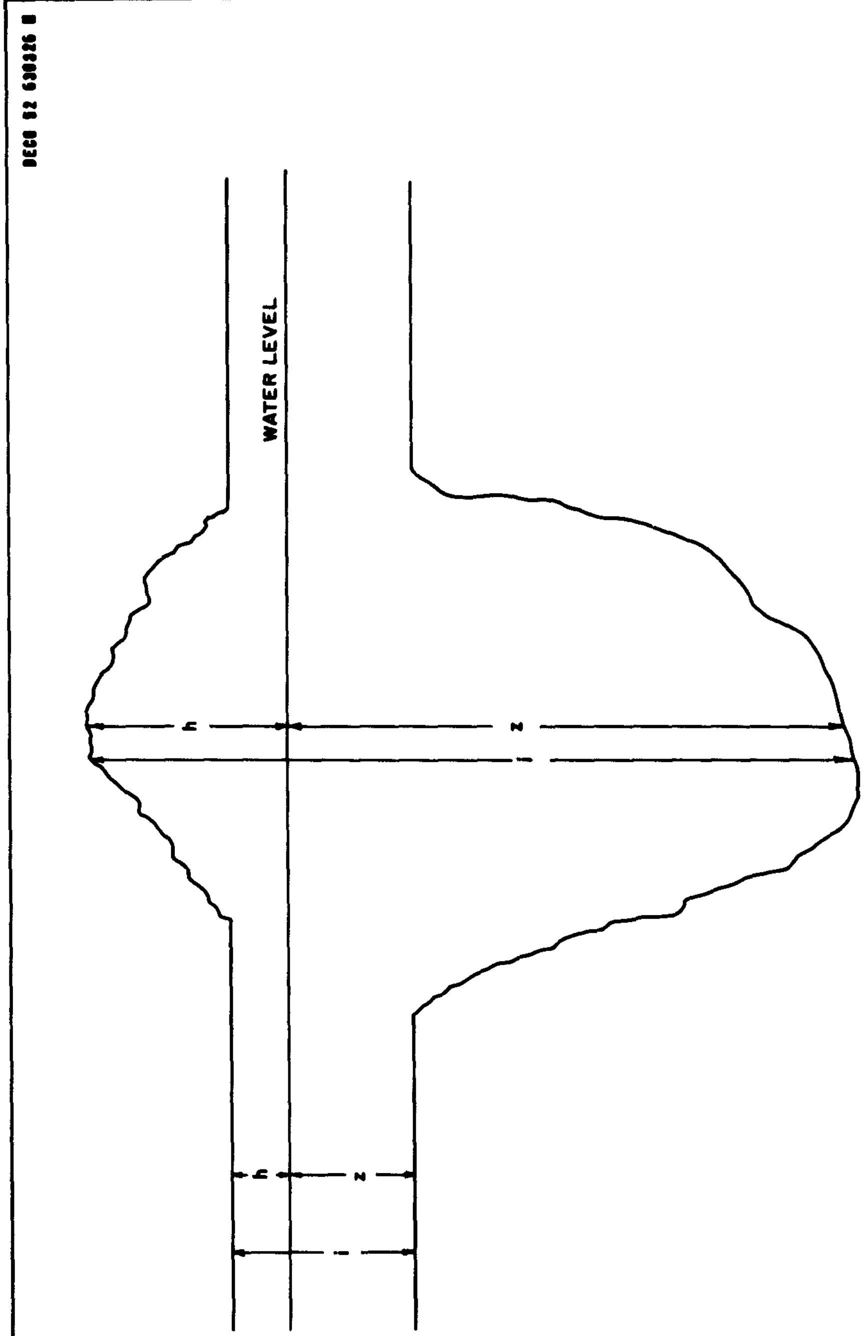

Figure 5-6 CROSS SECTION OF TYPICAL POLAR ICE FLOE

The proportion of h to z is determined by the density of the sea-ice and the density of the sea water in which the ice floats. Since these densities vary within rather narrow limits, the thickness of an unknown element can be easily approximated. The density of Arctic surface waters ranges between 1.01 and 1.03 while that of sea-ice ranges between 0.87 and 0.92.

Deformation of the ice occurs where ice is compacted, driven against the shore, or subjected to stresses resulting from steep thermal gradients between the top and bottom surfaces of the ice. Deformation results in the draining of salt and an interspersion of air spaces between fragments in both the above-water and under-water protuberances. For this reason the density relationships are modified somewhat for deformed ice. Table II shows the thickness relationships for various types of Arctic sea-ice.

TABLE II

Ratios for Estimating Ice Thickness and Height of Ridge from Measurements of Submerged Parts of Sea-Ice [Petrov, 1955]

	z/i	h/i	i/z	i/h	z/h	h/z
Level Polar Ice	0.83-0.86	0.17-0.14	1.20-1.17	6-7	4.9-6.1	0.20-0.16
Lightly Ridged Polar Ice	0.80-0.83	0.20-0.17	1.25-1.20	5-6	4.0-4.9	0.25-0.20
Ridged Polar Ice Fields	0.75-0.80	0.25-0.20	1.33-1.25	4-5	3.0-4.0	0.33-0.25
Heavily Ridged Polar Fields	0.67-0.75	0.33-0.25	1.50-1.33	3-4	2.0-3.0	0.55-0.33
Grounded Polar Floes	0.50-0.67	0.50-0.33	2.00-1.50	2-3	1.0-2.0	1.00-0.50

It should be cautioned that the relationships indicated in Table II are approximate but should yield sufficiently accurate results for estimating purposes.

6. SUMMARY

6.1 Factors and Precautions to Consider in Experimentation

The complexity of the structure of the ice sheet and the irreversibility of some of the formation processes, can create many pitfalls for the unwary research worker. A few are listed here for convenience. Others will undoubtedly occur to the careful investigator as he considers the effects of the various factors outlined in Section 3.

Weeks and Lee [1962] have published excellent advice concerning the significance of salinity determinations made at a test site: "Usually, when studies are performed on the physical properties of sea-ice, the scientific party arrives in the field a week to several months after the date of freeze-up. The ice surface is then covered with a layer of snow and little, if any, evidence is visible as to whether the ice-sheet under study was originally pure sheet-ice or some variety of pancake-ice. Tests are performed on the ice-sheet and salinity measurements are taken to represent the salinity of the test specimen. As was shown in the correlation analysis, unless the salinity of the specific volume of sea-ice that is involved in the physical test can be measured, the correlation coefficient between the test salinity and the salinity of nearby cores is no larger than would be expected if the values had been selected from a completely random population. For pancake-ice, however, since there is a significant increase in the variance around the mean as the sample spacing is increased, the standard deviation of the sampled population will be minimized by collecting salinity samples for the upper layer of the ice-sheet close to the test area. In sheet-ice and in the lower layers of pancake-ice below the thickness of the initial pancakes, there is no increase in variance as the sampling spacing is increased, and collecting the salinity samples close to the test site does not cause either an increase in correlation or a decrease in the standard deviation of the population of the sampled area."

Another uncertainty in salinity may be introduced in the process of securing ice samples for transportation to a laboratory located elsewhere. Not only will there be unavoidable brine drainage from the freshly exposed surfaces of the sample, but any temperature rise of the sample during transportation back to the laboratory can result in an outward migration of brine cells and a further loss of brine from the sample interior. If the sample is transported back to the laboratory at a temperature lower than the in situ value, then, when the sample is brought back to its in situ temperature in the laboratory, thermal gradients present during the warming process may cause outward migration of brine cells different from the inward migration which occurred during the cooling process. Thus an unpredictable brine loss may occur.

Another salinity error can occur if chlorinity measurements are used to determine salinity. The ratio of $So_4^=$ and Cl^- present in solution will vary with the temperature of the sample. Since drainage of this solution may occur over a wide range of temperatures, the $So_4^=/Cl^-$ ratio of specimens will depend upon their past histories. Hence chlorinity determinations cannot be used to calculate salinities unless the $So_4^=/Cl^-$ ratio is known for the particular specimen at its particular temperature.

As ice ages, the seasonal thermal cycling promotes crystal growth. Single crystals may become so large that an ice sample extracted for laboratory study will often sample only a single crystal. Thus, as the age of the ice increases, the sample volume must be made larger and larger if localized anomalies are to be averaged out. Otherwise the number of samples tested must be increased because of the increased scatter in the data.

The usual vertical orientation of brine cells results in a vertical electrical conductivity considerably greater than the horizontal electrical conductivity. If in situ determinations of electrical conductivity are attempted

using four-terminal-array methods, care must be exercised in the use of expressions for apparent conductivity of a layered medium since most of the expressions for apparent conductivity are derived on the assumption that the layers are electrically isotropic.

6.2 Areas Requiring Further Study

Knowledge of the electrical conductivity and permittivity of sea ice is so meager, almost any type of measurement in this area would be valuable. However, there would appear to be four main avenues of approach to the study of this material.

1) Studies of synthetic sea-ice. While the detailed behavior of synthetic ice will undoubtedly differ from that of genuine sea ice, the ease of preparation recommends its use in studying broad trends and pinpointing areas of detailed study on actual sea-ice.

2) Laboratory Study of Samples of Actual Sea-Ice. The sampling process is fraught with pitfalls, and the scatter in the data will undoubtedly be large. However, experiments can be performed with a complexity and a precision that would be practically impossible in the field. The details of the conduction and polarization mechanisms will undoubtedly be discovered by this approach.

3) Field Measurements on Actual Sea-Ice. The environment is at times extremely forbidding, and experiments would have to be performed under the most difficult of circumstances. However, this approach is the only one which would give the average electrical properties of large volumes of ice. The presence of an underlying conducting stratum so close to the surface will seriously complicate the interpretation of four-terminal conductivity data obtained by this method.

4) Development of a Theoretical Model. Anderson and Weeks [1958] have developed an idealized brine cylinder model which has given a measure of success in explaining observed mechanical properties. Such a model, with refinements, must be used for the calculation of the electrical properties.

More specifically, there is need for field measurements of the electrical conductivity and permittivity, from DC up to microwave frequencies as a function of the temperature and salinity. For bulk measurements on large volumes of ice, average salinities and temperatures should suffice. Determinations of both horizontal and vertical values of σ and ϵ' (averages) should be made .

More detailed laboratory measurements should be made on smaller samples also. If these specimens are sufficiently small, the salinity and temperature values will be constant throughout the entire sample. Such a detailed knowledge of σ and ϵ', where brine cell dimensions, sulphate/chloride ratios, crystal orientation, and crystal sizes can all be carefully determined, would be extremely valuable in analysing the large amounts of scatter that field measurements will undoubtedly reveal.

Finally, there is need for several isolated studies of a more basic type which would be useful in connection with the development of a theoretical model for sea-ice. In this category should be included: (1) The electrical conductivity of brine at the temperatures and concentrations normally found in sea-ice (page 38); (2) The effect of impurities on the dielectric absorption of solid salts and the nature of the second absorption peak found in such salts (page 37); (3) The amount of dielectric absorption found in all of the solid salts existing in sea ice, with particular attention to the effect of their water of hydration (page 38); and (4) A search for the existence of so-called 'mixed-crystals' in sea-ice. If such exist, the impurities built into the ice structure will produce a broadening of the usual Debye type of absorption found in pure ice (page 36).

An understanding of these basic properties of the constituents of sea-ice would be very helpful in the development of a suitable model for predicting the electrical properties of sea-ice.

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Appendix A: ICE NOMENCLATURE

Different specimens of sea-ice may experience quite different thermal histories and hence may possess quite different structures and shapes. Because so many different forms and configurations have been noted by explorers, a highly specialized but not always consistent terminology has developed over the years. In addition, different nations, in making ice reconnaissance reports, have developed their own ice reporting codes. Each country, with characteristic nationalism has then proceeded to advocate its own nomenclature and code for international adoption*.

The World Meteorological Organization has recently succeeded in establishing a single international nomenclature and the Commission for Maritime Meteorology of the WMO is presently working on proposals for unified international working codes. Mr. John J. Schule Jr., U.S. Navy Hydrographic Office, is the chairman of the working group of the commission responsible for the establishing of codes for the exchange of ice information between countries. Accompanying the WMO nomenclature is an official set of 82 illustrations of the various ice types and forms**. For convenience, a part of the WMO nomenclature, in abridged form, and without illustrations, is reproduced here.

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* The Proceedings of the Arctic Sea-Ice Conference, NAS-NRC Publication 598, gives good examples of nomenclature (USSR pp. 11-14, U.K. pp. 22-28, and reporting codes (Japan pp. 39-47, Sweden pp. 57-68, U.S.A. pp. 69-57)

** A complete set of eighty-two 4" x 5" glossy prints is available for 80 Deutschmarks (approximately $19.00) from:

Foto haus
Friedrich Kunze
2000 Hamburg 36
Stephanplatz 2
Germany

DEFINITIONS OF ICE TERMS

(From Abridged International Ice Nomenclature)

ANCHOR ICE/GROUND ICE
: Ice found attached or anchored to the bottom, irrespective of nature of its formation

ARCTIC PACK
: Almost salt-free ice, having existed over two years. Thickness up from 2.5 m. The ice surface is undulating. Its hummocks having melted more than once are therefore smoothed. In case of absence or insignificant thickness of snow cover, this ice is coloured in different tints of blue

BARE ICE
: Ice without snow cover

BARRIER BERG
: See Tabular berg

BAY/BIGHT
: An inward bend of the ice-edge, formed either by wind or current

BAY-ICE
: Level ice of more than one winter's growth, which has remained unhummocked and also becomes nourished by surface layers of snow. Thickness of ice and snow up to about 2 m above sea level.

BELT
: Long area of pack-ice/drift ice from a few kilometers to more than 100 kilometers in width

BERGY-BIT
: A medium-sized piece of ice, generally less than 5 m above sea level and about the size of a small cottage, mainly originating from glacier-ice, but occasionally a massive piece of sea-ice or disrupted hummocked ice. When the sea-ice origin is not in doubt the term FLOEBERG may be used.

BIG ICE-FLOE
: See Ice-floe

BIGHT
: See Bay

BRASH-ICE
: Accumulation of small fragments not more than 2 m across, the wreckage of other forms of ice

CLOSE PACK-ICE/DRIFT ICE
Composed of floes mostly in contact. Ice cover 7/10-9/10 or 6/8-7/8

CRACK
Any fracture or rift in sea-ice not sufficiently wide to be described as a lead/lane. It is usually possible to jump across a crack

DRIED ICE
Ice surface, from which the water has disappeared after the formation of cracks and holes. During the period of drying, the surface is whitening

FAST-ICE
Sea-ice which remains fast, generally in the position where originally formed, and which may attain a considerable thickness. It is found along coasts, where it is attached to the shore, or over shoals, where it may be held in position by islands, grounded icebergs or grounded polar ice

FIRN SNOW/NEVE
Snow which has become coarse-grained and compact through temperature changes, forming the transition stage to glacier-ice

FLOE
See Ice-floe

FLOEBERG
See Bergy-bit

FRAZIL CRYSTALS
See Ice crystals

FROST SMOKE
Fog-like clouds, due to the contact of cold air with relatively warm sea water, which appear over newly-formed leads/lanes and pools, or leeward of the ice-edge, and which may persist while slush or sludge and young ice are forming

GLACIER BERG
Mass of glacier-ice which has broken away from its parent formation on the coast, and either floats, generally at least 5 m above sea level, or is stranded on a shoal

GLACIER-ICE
Any ice floating on the sea as a berg, which originates from a land glacier

GLACIER TONGUE
Projecting seaward extension of glacier, usually afloat. In the Antarctic glacier tongues may extend over many tens of kilometers

GROUNDED HUMMOCK
Hummocked ground ice formation. There are single grounded hummocks and lines (or chains) of grounded hummocks

GROUND ICE
See Anchor ice/Ground ice

GROWLER
Smaller piece of ice than a bergy-bit, frequently appearing greenish in colour and barely showing above water. May originate both from sea-ice and from glacier-ice

HUMMOCK
Ice pieces piled one over another on a rather smooth ice surface

HUMMOCKED ICE
Ice piled haphazardly one piece over another

ICE-BAR
Ice-edge consisting of floes compacted by wind, sea and swell, and difficult to penetrate

ICEBERG
Large mass of floating or stranded ice, more than 5 m above sea level, which has broken away either from a glacier or from an ice-shelf formation. Sub-divisions are GLACIER BERG and TABULAR BERG/BARRIER BERG

ICE-BLINK
A typical whitish glare on low clouds above an accumulation of distant ice. It is especially glowing when observed on the horizon.

ICE BRECCIA/ICE MOSAIC
Ice pieces of different age frozen together

ICE-CAKE
A floe smaller than 10 m across. One less than 2 m across may be termed a small cake (See Brash-ice)

ICE CRYSTALS/FRAZIL CRYSTALS
Fine spicules or plates of ice, suspended in water

ICE-EDGE
The boundary at any given time between the open sea and sea-ice of any kind, whether floating or fast

ICE-FIELD/FIELD OF ICE

Area of pack-ice/drift-ice, consisting of any size of floes, of such extent that its limits cannot be seen from the crow's nest

ICE-FLOE/FLOE

A single piece of sea-ice, other than fast-ice, large or small, described if possible as "Light" or "Heavy" according to thickness

Vast	- over 10 km across
Big	- 1 - 10 km across
Medium	- 200 - 1000 m across
Small	- 10 - 200 m across

ICEFOOT

Ice step attached to the coast, unmoved by tides and remaining after the fast-ice has moved away. Several varieties of icefoot can be distinguished

ICE ISLAND

Drifting portion which has separated off from an ice-shelf

ICE LIMIT

Average position of the ice-edge in any given month or period based on observations over a number of years

ICE MOSAIC

See Ice breccia/ Ice mosaic

ICE-RIND

A thin, elastic, shining crust of ice, formed by the freezing of slush or sludge on a quiet sea surface. Thickness less than 5 cm. It is easily broken by wind or swell, and makes a tinkling noise when passed through by a ship

ICE-SHELF

Ice formation over 2 m above sea level with level surface, which originates from annual accumulations of firn-snow/neve layers on bay-ice (or on the seaward extension of a glacier)

ICE-SLUSH

An accumulation on the surface of the water of ice needles frozen together; it forms patches or a thin compact layer of a greyish or leaden-tinted colour. The surface of the sea covered with ice-slush has a dim tint

LANE

See Lead

LARGE ICE-FIELD/FIELD OF ICE
An ice-field over 20 km across

LEAD/LANE
A navigable passage through pack-ice/drift ice

LEVEL ICE
Ice with a flat surface, which has never been hummocked; typical with regard to bays, gulfs, straits, archipelagoes and shallow waters, where the ice formation occurs in undisturbed conditions

MEDIUM ICE-FIELD/FIELD OF ICE
An ice-field 15 - 20 km across

MEDIUM ICE-FLOE
See Ice-floe

MEDIUM WINTER-ICE
Winter-ice of thickness 15 - 30 cm

NEVE
See Firn-snow

NEW ICE
A general term which includes Ice crystals/Frazil crystals, Slush, Sludge, Pancake ice and Ice-rind

OPEN ICE-EDGE
Unsteady and not sharply outlined ice-edge, limiting an area of open ice; in most cases it is to leeward

OPEN PACK-ICE/DRIFT ICE
Floes seldom in contact with many leads and pools. Ice cover 4/10 - 6/10 or 3/8 - 5/8

OPEN WATER
A relatively large area of free navigable water in an ice-encumbered sea

PACK-ICE/DRIFT-ICE
Term used in a wide sense to include any area of sea-ice, other than fast-ice, no matter what form it takes or how disposed

PANCAKE ICE
Pieces of newly-formed ice, usually approximately circular, about 30 cm to 3 m across, and with raised rims, due to the pieces striking against each other, as the result of wind and swell

PATCH

A collection of pack-ice/drift-ice, less than 10 km across, the limits of which are visible from the crow's nest

POLAR FAST-ICE

Fast-ice formed by the grounding and cementing together of polar ice. By the end of the winter it may reach some tens of kilometers from the coast

POLAR ICE

Extremely heavy sea-ice, up to 3 m or more in thickness of more than one winter's growth. Heavily hummocked and may ultimately be reduced by weathering to a more or less even surface. Polar ice may be sub-divided into YOUNG POLAR ICE and ARCTIC PACK

POLYNYA

Water area enclosed in ice, generally fast; this water area remains constant and has usually an oblong from. Sometimes the polynya is limited on one side by the coast.

POLYNYA OFF EDGE OF SHORE ICE

Polynya between shore ice and drift-ice, formed by squeezing winds and currents

POOL

Any enclosed relatively small sea area in pack-ice/drift-ice other than a lead/lane

PRESSURE-ICE/SCREW-ICE

A general term for ice which has been squeezed together and in places forced upwards. Sub-divisions are RAFTED ICE, HUMMOCKED ICE and PRESSURE RIDGE

PRESSURE RIDGE

Ridge or wall of hummocked ice where floes have been pressed against each other

PUDDLE

See Snow water on the ice/Puddle

RAFTED ICE

Type of pressure-ice/screw-ice formed by one floe over-riding another

RAM

An underwater ice projection from an iceberg or a hummocked ice-floe. Its formation is usually due to a more intensive melting of the unsubmerged part of the floe

ROTTEN ICE

Ice which has become honeycombed in the course of melting and which is in an advanced state of disintegration

SCREW-ICE

See Pressure-ice

SHORE ICE

Basic form of fast ice, representing a compact ice cover attached to the shore and, in shallow waters, also grounded; during changes of sea level vertical fluctuations can be observed. Shore ice can spread in breadth up to several hundreds of kilometers

SHORE LEAD

A lead between pack-ice/drift-ice and the shore, or between pack-ice/drift-ice and a narrow fringe of fast-ice

SHORE POLYNYA

Polynya along the coast, formed either by current or wind

SLUDGE

Spongy whitish ice lumps, a few centimeters across; they are formed of slush, of snow slush and sometimes of spongy ice lumps formed on the bottom of the sea and emerging on the surface

SLUSH OR SLUDGE

An accumulation of ice crystals which remain separate or only slightly frozen together. It forms a thin layer and gives the sea surface a greyish or leaden-tinted colour. With light winds no ripples appear

SMALL ICE-CAKE

An ice-cake less than 2 m across

SMALL ICE-FIELD/FIELD OF ICE

An ice-field 10 - 15 km across

SMALL ICE-FLOE

See Ice-floe

SNOW-COVERED ICE

Ice covered with snow

SNOW SLUSH

Viscous mass formed as a result of a thick snow fall into cooled water

SNOW WATER ON THE ICE/PUDDLE

Ice the surface of which is covered with snow water, i. e. an accumulation on the ice of melt-water, mainly due to snow melting. The stages of development of snow water are as follows: patches of melting snow, puddles on the ice - small and shallow accumulations of melt-water on the ice, larger amounts of water, which have deepened on account of ice melting and which have sharply-defined outlines

STANDING FLOE

A separate floe standing vertically or inclined and enclosed by rather smooth ice

STEAM/STRIP/STRING

Long narrow area of pack-ice/drift-ice, about 1 km or less in width, usually composed of small fragments detached from the main mass of ice, and run together under the influence of wind, swell or current

STRING

See Stream

STRIP

See Stream

TABULAR BERG/BARRIER BERG

A flat-topped berg, showing horizontal firn-snow/neve layers, usually broken off from an ice-shelf formation

THAWING HOLES IN THE ICE

Ice with open holes in it, usually of a circular form; these holes are a further stage of development of snow waters by ice melting

THICK WINTER-ICE

Winter-ice more than 30 cm thick

TIDE CRACK

Crack formed between shore ice and the icefoot under the action of the fluctuations of the sea level. Typical only for shore ice areas

TONGUE

A projection of the ice-edge up to several kilometres in length, caused by wind or current

VAST ICE-FLOE

See Ice-floe

VERY CLOSE PACK-ICE/DRIFT ICE

Ice cover practically 10/10 or 8/8 and little if any water present

VERY OPEN PACK-ICE/DRIFT-ICE

Water preponderates over ice. Ice cover 1/10 - 3/10 or 1/8 - 2/8 (formerly known in Britain as "drift-ice")

WATER-SKY

Typical dark patches and strips on low clouds over a water area enclosed in ice or behind its edge. It is due sometimes to an open water area out of the limits of visibility

WEATHERED ICE

Hummocked polar ice subjected to weathering which has given the hummocks and pressure ridges a rounded form. If the weathering continues, the surface may become more or less even

WINTER FAST-ICE

Fast-ice in fjords, gulfs and straits, mainly formed by growth from the shore, but also by cementing of pack-ice/drift-ice. Winter fast-ice rises and falls according to the tide.

WINTER-ICE

More or less unbroken level ice of not more than one winter's growth, originating from young ice. Thickness from 15 cm to 2 m. Completely safe for travelling purposes. Winter-ice may be sub-divided into MEDIUM WINTER-ICE and THICK WINTER-ICE

YOUNG ICE

Newly-formed level ice generally in the transistion stage of development from ice-rind, or pancake ice to winter-ice; thickness from 5 cm to 15 cm, as a rule impassable and unsafe for travel either by men or dogs, or in the case of aircraft for ski or wheel landings.

YOUNG POLAR ICE

Polar ice which has not melted during the first summer of its existence and which has passed over to the second phase of increase. At the end of the second winter, it attains a thickness up to 2 m and more. It differs from ice one year old by a greater portion showing above the surface of the water and also by the hummocks on it being smoother

YOUNG SHORE ICE

Primary stage of formation of shore ice; it is of local formation (at shore) and usually consists of ice-rind or thin young ice; usually some 10 m in width, but sometimes even more (100 - 200m).

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Appendix B: SOURCES OF INFORMATION ON SEA-ICE

Major Establishments

Major centers of activity and information on the properties of Arctic ice are as follows:

1. U. S. Army Cold Regions Research and Engineering Laboratory, Hanover, New Hampshire

   This laboratory, replacing the old "Snow, Ice, and Permafrost" Research Establishment of the Corps of Engineers, in Wilmette, Illinois, is the most extensive and well equipped in this country.

   Among the work being done there are studies concerning the mechanical properties of sea-ice. This research shows a level of analysis and a degree of theoretical sophistication almost entirely lacking in the more empirical studies of Russian workers.

   As a part of its library facility, the laboratory maintains an abstract index presently numbering some 20,000 items. Annual additions to this index are published as the bibliography on Snow, Ice, and Permafrost, and are available from ASTIA (see Bibliographies and Indexes). Contact with this laboratory is possible through Dr. A. Assur, Chief, Applied Research Branch, and Dr. W. W. Weeks, Materials Research Branch.

2. Arctic Institute of North America, 3458 Redpath Street, Montreal 25, Quebec (Main Library), or 1530 P. St., N. W., Washington 5, D. C.

   The Institute serves primarily as a clearing house for information on every facet of the Arctic. It maintains a

very extensive library and map collection at the Montreal Office, accepts research contracts, awards research grants, and publishes the Journal, Arctic, and the Arctic Bibliography.

3. U. S. Navy Electronics Laboratory, Arctic Sciences and Technology Division, Building 371, San Diego 52, California

NEL maintains a very complete facility for Arctic studies including a large sea-water tank in which arctic temperature conditions can be carefully reproduced, and sea-ice readily synthesized. Contact with this laboratory is possible through Dr. E. M. Little, Code 3120, and Dr. Waldo K. Lyon.

4. Arctic Research Laboratory, Point Barrow, Alaska

Established and operated by the Office of Naval Research, as a field station, the laboratory provides quarters, shop facilities and basic logistics support for agencies or contractors wishing to investigate Arctic phenomena. Detailed information on facilities and procedures is contained in an Information Handbook for Contractors and Prospective Contractors for Research Projects at the Arctic Research Laboratory, Point Barrow Alaska, available from the Director of the Arctic Research Laboratory, Box 1310, Fairbanks, Alaska.

5. The Stefansson Library

This is one of the most extensive collections of arctic literature available in this country, and contains many translations of Russian material unavailable elsewhere. It was assembled over a period of many years by the famous arctic explorer Vilhjalmur Stefansson and kept in New York City. Prior to his death in 1962, Steffansson donated his

entire library to Darmouth College, in Hanover, N. H., where it remains at present as a collection in the Baker Library.

Bibliographies and Indexes

1. Arctic Bibliography, Volumes I to X, prepared by the Arctic Institute of North America

   This is the most extensive bibliography available on the arctic, covering not only all aspects of physical science, but also the life sciences, history, and politics of the arctic regions.

2. Bibliography on Snow, Ice, and Permafrost, Volumes I-XVI, prepared by the Science and Technology Division of the Library of Congress under agreement with USA SIPRE or USA CRREL (Item 1 under Establishments)

   The bibliography is available through ASTIA or the Office of Technical Services under the numbers listed below, and gives a very complete summary of research in the field of snow, ice and permafrost, as found in reports of government agencies and contractors, and in domestic and foreign periodicals. It covers all existing literature back to 1930, and includes pertinent references to even earlier material. Volumes I through XI were issued semiannually beginning in 1951. Volumes XII through XVI have been published annually. Entries contain an abstract of the original article, plus a designation of major libraries where the original may be found.

Vol. I	TIP U 21020	Vol. IV	AD 23334
Vol. II	TIP U 24230	Vol. V	AD 29227
Vol. III	AD 11941	Vol. VI	AD 42727

Vol. VII	AD 57394	Vol. XII	PB 133866
Vol. VIII		Vol. XIII	
Vol. IX		Vol. XIV	AD 255 755
Vol. X	PB 125902	Vol. XV	
Vol. XI	PB 130788	Vol. XVI	

3. The Polar Bibliography - Volumes (I - III), produced by the former Technical Information Division of the Library of Congress for the Department of Defence

   It is "based on materials not published through the normal commercial media. These include formal reports, staff studies and memoranda for the record, as well as other unpublished papers, translations, pamplets, manuals, and books prepared by the military or their contractors and issued since 1939." Documents are listed by AD, TIP, or ATI number if they are obtainable from ASTIA, or by PB number if available for sale at the Office of Technical Services, Department of Commerce, Washington, D. C. The three volume bibliography is numbered in several ways: AFM 200-132; DA pamphlet 70-1, 70-2, 70-3; OPNAB Instructions 3470. 3; NAVMC 1127; or ASTIA documents AD 109388, AD 121911, AD 229786.

4. The Classified Polar Bibliography (1 Volume)

   A companion volume to the three volumes listed above, but containing classified references.

5. Antarctic Bibliography -prepared for the U. S. Navy by the Bureau of Aeronautics in 1951.

6. Bibliographic Series 28 of the Quatermaster Research and Development Laboratories, by F. D. Horigan

   39 references dealing with electrical characteristics of snow and ice.

7. SIPRE Report 4

Review of the Properties of Snow and Ice. Prepared by the Engineering Experiment Station staff of the University of Minnesota in July 1951, to provide background material for workers in the field of snow and ice research. The compilation of material is excellent, but the information on fresh ice far exceeds that presented for sea-ice.

8. Ice Atlas of the Northern Hemisphere - Available as HO 550 from the U. S. Hydrographic Office, Washington 25, D. C. ($5.00).

This 24" x 24", 105 page atlas was last corrected in 1955. It provides detailed charts of all northern regions that have been explored and gives seasonal variations, limits and types of ice that have been reported. It gives an extensive bibliography of 1700 references to arctic ice, from which the chart information has been drawn.

9. Oceanographic Atlas of the Polar Seas, Part II, Arctic, 1958, H. O. Pub. 705 ($5.00)

This 12" x 16", 150 page atlas summarizes "the oceanographic knowledge of the arctic available prior to the International Geophysical Year 1957-58". Main subdivisions include: Tides and Currents, Physical Properties (of the arctic ocean), Ice (seasonal limits and distribution), Wind, Sea, and Swell, Marine Geology, Marine Biology, Distribution of Oceanographic Observations, and Bibliography. The bibliography contains 124 entries, all of which are additional to those mentioned above in H.O. 550.

Indexes

In addition to the bibliographies, which, by their very nature, are focussed on phenomena of the arctic or antarctic, it may sometimes

be necessary to search through several of the more important indexes or abstracts if the phenomena under study are likely to receive academic attention, but under such circumstances that they would not be of interest to the arctic bibliographers. Searches through the following should prove particularly useful:

Geophysical Abstracts
Meteorological and Geoastrophysical Abstracts
Engineering Index
Japanese Periodicals Index (Natural Sciences)
Applied Science and Technology Index
Technical Translations (Translations from Russian periodicals prepared by Dept. of Commerce)

Pertinent Books

1. Morskie Vody i l'dy, Gidrometeoizdat, Moskava (1938) (Marine water and ice, Hydrometeorological Publishing House, Moscow) by Nikola Nikolaivitch Zubov

   An early, rather descriptive treatment of the subject of the arctic ocean and its ice cover by the noted Russian Arctic explorer, Zubov. A translation of this book is on file in the U.S. Hydrographic Office, Suitland, Maryland, and also in the Stefansson Collection, Hanover, N.H.

2. L'dy Arktiki, Izdatel'stvo Glavsevmorputi, Moskova (1945) N.N. Zubov (Arctic Ice, Norther Sea Route Administration Publishing House, Moscow (1945))

   A later, improved, but smaller book by the same author, it is the most complete work in existence today on the subject of arctic ice. It contains 13 chapters and approximately 80 figures and tables. Main subject divisions are as follows:

   The properties of sea water
   Changes in the temperature and salinity of the ocean
   Mixing of ocean waters
   Ice formation and varieties of sea ice

Physical and chemical properties of sea ice
Growth of sea ice
Deformation of sea-ice
Thawing of sea-ice
Tidal phenomena
Sea currents
Wind, and ice drift
Circulation of water and ice in basins
Seasonal and long-range fluctuations of ice cover

The book contains a bibliography of 179 references, mostly to Russian works. An informative review of this book has been given by Shumkin (1949). A rather free translation has been prepared by the Stefansson Library under the auspices of SIPRE. Copies are known to be on file in the Weather Bureau Library, Building F. O. -4, Suitland Maryland, and also in the Stefansson Collection, Hanover, N. H.

3. Oceanological Tables, by N. N. Zubov, Library of Congress No: GC 51 Z79

Tables of most of the physical constants of sea-ice and sea water. (But not including electrical properties of ice). Text in Russian.

4. Encyclopedia Arctica

Listed in abstracts as being in preparation by ONR in 1949, photostats of a partial manuscript of this extensive treatment (Vol. 7 only) are on file in the Weather Bureau Library, Suitland, Maryland.

5. Physical Oceanography, 2 Vols., A. Defant, Pergamon Press (1961)

The most extensive work in English on the subject of physical oceanography, this translation from the German covers the oceanographic literature up to May 1957.

Volume I is concerned with the physical characteristics and circulation of the earth's water envelope and polar ice cover. Volume II treats waves, tides and related phenomena. A chapter on sea-ice in Volume I covers: formation and terminology of sea-ice, physical and chemical properties of sea-ice, ice conditions and their seasonal and aperiodic variations in Arctic and Antarctic regions, land ice in the sea, and effect of polar ice conditions on the atmospheric and oceanic circulation.

6. The Oceans, H. U. Sverdrup, M. W. Johnson, R. H. Fleming, Prentice Hall, (1942), 10th printing, 1961.

   A definitive work in English on the physics, chemistry and general biology of the oceans, its discussion of sea-ice is limited to a few pages in the chapter on physical properties of sea water.

7. Arctic Sea Ice, National Academy of Science, National Research Council, Publication 598 (1958) $4.00

   This proceedings of the Arctic Sea Ice Conference held at Easton, Maryland, February 1958, is extremely useful to the neophyte seeking an introduction to the characteristics and problems of the arctic. It is equally valuable to the seasoned investigator of arctic problems seeking the latest information on various aspects of arctic research. Main topics covered are:

   Distribution and character of sea-ice
   Sea-ice observing and reporting techniques
   Physics and mechanics of sea-ice
   Sea-ice formation, growth, and disintegration
   Drift and deformation of sea-ice
   Sea-ice prediction techniques
   Sea-ice operations

The material presented is supported by some 300 references.

8. V Tsentrali Arktiki, (In the Center of the Arctic) by N. N. Zubov (1948)

A rather nationalistic account of Soviet Arctic expeditions, the conditions encountered, and the physical mechanism explored or revealed. Portions of this book have been translated by the Stefansson Library and are on file there. Included in this translation are chapters on:

Station North Pole - pp. 64-74
Drift of the Icebreaker SEDOV - pp. 79-89
Sea-Ice - pp. 166-179
Ice-drift - pp. 188-213

Copies of this translation are available from ASTIA under AD141181. This book has also been translated by E. Hope, DRB, Dept. of Defence, Ottawa, Canada.

9. Sea Ice, A. Boorke, Polar Workers Library, Moscow (1940)

A rather short, quite descriptive, but very informative work on the following:

Formation of ice at sea
Properties and peculiarities of sea-ice
Thawing of ice
Dynamics of the ice cover and its might
Classification of seas according to ice regime
Categories and types of ice formations

This book has been translated from the Russian by the Stefansson Library and is on file there. Copies of the translation are available from ASTIA under AD141181.

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Appendix C: DISCUSSION OF SALINITY AND CHLORINITY

Definitions and Relationships

The simplest definition of salinity would be one which involved the total weight of dissolved salts present in 1 kilogram of sea-water. However, in the process of evaporating the sea water to recover the dissolved salts for weighing, some of the material present, particularly the bromides and iodides may be partially removed along with the steam. Therefore, at the suggestion of Forch, Sorenson, and Knudsen (1902), the salinity has come to be defined as "the total amount of solids in grams, contained in 1 kilogram of sea-water when all the bromine and iodine has been replaced by the equivalent amount of chlorine, all the carbonate converted to oxide, and all organic matter has been completely oxidized." Since salinity is expressed in "per thousand" rather than in "per cent" the symbol 0/00 is adopted.

Measurement Techniques

In practice, in the field, the sample is titrated with silver nitrate using calcium chromate solution as an indicator, after the method developed by Meyer (1932). This fast and accurate procedure measures the chlorine in sea-water, expressed as chlorinity, $C\ell$, in parts per thousand (0/00). Knudsen (1902) has shown that salinity is directly related to chlorinity by the relation $S = 0.030 + 1.8050\ C\ell$.

In these determinations of salinity by means of the chlorinity measurement, values obtained are relative unless the titrating solution has been standardized. This standardizing is done by comparing the titration of the unknown sample against a titration using "standard water". This "standard water" is carefully prepared by the Woods Hole Oceanographic Institution according to a recipe introduced by Knudsen (Cir. No. 87) and its chlorinity has been very accurately

determined.

The preparation of "standard water" is meaningful because measurements have shown (Thompson) that while the salinity varies widely throughout the oceans of the earth, the relative proportions of the various ions present remains remarkably constant. It is for this reason that the chlorinity and salinity determinations are so simply related.

Preparation of Artificial Sea Water

Clarke (1924) has shown that, for purposes of laboratory experimentation, artificial sea-water of salinity 32 0/00, approximately that of the Arctic Ocean, may be prepared from the following simple receipe:

distilled H_2O	3000 $m\ell$
$NaC\ell$	82.5 g
$MgSO_4$	10.6 g
$MgC\ell_2$	6.14 g
$CaC\ell_2$	3.3 g
$KC\ell$	0.83 g
K_2CO_3	0.7 g

Other receipes which concentrate attention on trace elements involved in particular research interests are given by Sverdrup, Johnson and Fleming (1942).

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Sverdrup, H.U., M. W. Johnson, and R. H. Fleming, The Oceans, p. 186, Prentice Hall (1942)

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